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TTCS System Design Description

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TTCS SYSTEM DESIGN DESCRIPTION

1 Scope of the document

The objective of this document is to describe the Tracker Thermal Control System (TTCS) and the operation principles of the TTCS. Details on components can be found in the component specifications.

1.1 Reference documents

RD-1	Combined proposal Development of the Tracker Thermal Control System of the Alpha Magnetic Spectrometer, SYSU/NLR/INFN, J. van Es, B. Oving, R. van Benthem, July 2004.	NLR-ASSP-2004-021 Issue 1
RD-2	Requirements for the manufacturing and space qualification of all the pressurised weld joints in the AMS TTCS evaporator, revision B, B. Verlaat, 2 Sept. 2003	ASR-S-001
RD-3	NASA- document “Simplified Design Options for STS-Payloads”	JSC-2045RevA
RD-4	TTCS Heater Specification	AMSTR-NLR-TN-043 Issue 4.0
RD-5	AMS02 TTCE Interface Control Document	AMSTR-NLR-TN-24 Issue 4.0
RD-6	TTCS Safety Approach	AMSTR-NLR-TN-044 Issue 2.0
RD-7	TTCS Condenser Freezing Test Report	AMSTR-NLR-TN-039 Issue03
RD-8	TTCS Condenser High Pressure Test	AMSTR-NLR-TR-007 Issue 1.0
RD-9	TTCS Leak rate	AMSTR-NLR-TN-046 Issue 1.0
RD-10	TTCS Filling system and accuracy	AMSTR-NLR-TN-019 Issue 2.0
RD-11	TTCS Modelling Description	TTCS-SYSU-SIMU-PR-002 Issue 2.0
RD-12	TTCS Box Temperature Requirements	AMSTR-NLR-TN-31 Issue02
RD-13	TTCS Thermal Analysis Results	TTCS-SYSU-SIMU-PR-003 Issue 1.0
RD-14	AMS-02 Tracker Thermal Control System (TTCS) Cold Environment Temperatures	ESCG-4470-06-TEAN-DOC-0032
RD-15	TTCB FM Vibration test procedure	AMSTR-NLR-PR-030 Issue 3.0
RD-16	TTCB EMC/EMI operation procedure Part B	AMSTR-NLR-PR-029 PARTB Issue 1.0
RD-17	TTCS Test Report for Micro-g 2nd Loop Performance test	AMSTR-SYSU-TRP-04-iss1.0

RD-18	TTCS Test Report for Micro-g 1st Loop Performance test	AMSTR-SYSU-TRP-05-iss1.0
RD-19	TTCS EM Test Report for both 1st and 2nd Loop in 3D lay-out	AMSTR-SYSU-TRP-010-iss1.0
RD-20	TTCS QM Test Report for 2nd Micro-g Loop Performance Test	AMSTR-SYSU-TRP-016-iss1.0
RD-21	TTCB Primary Drawing package	ET5998-06 Release 15-09-2009
RD-22	TTCB Secondary Drawing package	ET5998-08 Release 15-09-2009
RD-23	Revised requirements for the pumps of the AMS Tracker Thermal Control System (TTCS)	AMSTR-NL-TN-010 Issue 04
RD-24	PDT pump proposal, TP-5059-2, “AMS Tracker Thermal Control System Pump”	TP-5059-2, Revision B, 03-SEP-2004
RD-25	TTCS Accumulator Specification	AMSTR-NLR-TN-18-Issue03
RD-26	Design of TTCS Accumulator	AMS02-CAST-TTCS-ACC-DR-002
RD-27	TTCS Heat Exchanger Design	AMSTR-NLR-TN-053 Issue 1.0
RD-28	TTCS Radiator & Condenser Simulation Results	AMSTR-SYSU-SIMU-PR-005-1.0
RD-29	TTCE software user requirements document	AMSTR-NLR-TN-034 Issue 3
RD-30	TTCS Component list	ComponentsList_16_09_V51.xls
RD-31	Detailed cabling Schematic	ttcs_harness_rev4.9.pdf

2 AMS Introduction

2.1 Alpha Magnetic Spectrometer (AMS)

The Alpha Magnetic Spectrometer (AMS) is a space born detector for cosmic rays built by an international collaboration. AMS will operate aboard the truss of the International Space Station (ISS) for at least 3 years, collecting several billions of high-energy protons and nuclei. The main goal is to search for cosmic antimatter, (that is for anti-helium nuclei primarily), for dark matter and lost matter.

A first version of the detector, known as AMS-01, flew aboard the Space Shuttle Discovery during the STS-91 mission (2-12 June 1998), collecting about hundred millions of cosmic particles. This trial mission confirmed the main ideas of the project and gave important suggestions for further development.

For the ISS mission, the detector will be slightly different in concept, achieving a higher resolution. In fact, AMS-02 will be an “improved” version of AMS-01. The solid magnet of the AMS-01 mission will be replaced by a more powerful Helium cooled super-conductive cryo-magnet in AMS-02. The introduction of the cryo-magnet does not only introduce additional magnet cooling, it also increases the thermal design complexity of the Tracker Thermal Control System (TTCS).

In AMS-01, the massif solid magnet was used to collect the heat produced by the Tracker electronics. The strict temperature stability requirements could be easily met due to the good thermal connections from the electronics to the magnet that has a very large heat capacity. In AMS-02, the super-conductive magnet does not provide this large heat capacity and therefore an active thermal design is required to meet the stringent electronics temperature stability requirements.

2.2 Tracker Thermal Control System for AMS-02

The AMS-02 Tracker Thermal Control System (TTCS) is a two-phase cooling system developed by NIKHEF (The Netherlands), Geneva University (Suisse), INFN Perugia (Italy), Sun Yat Sen University Guangzhou (China), Aerospace Industrial Development Company (Taiwan) and NLR (The Netherlands). The TTCS is a mechanically pumped two-phase carbon dioxide cooling loop. The main objective is to provide accurate temperature control of AMS Tracker front-end electronics. An additional objective is to prove and qualify a two-phase pumped cooling system in orbit and collect operational data in micro-g environment over a period of three years.

The objective of the cooling system is to collect the dissipated heat at the tracker electronics and transport the heat to two dedicated heat pipe radiators. One radiator is located at the top WAKE (anti-flight direction) side and the other one at the RAM (flight direction) side of the AMS instrument.
The two-phase loop incorporates a long evaporator, picking up the heat from the multiple heat-input stations evenly distributed over the six Tracker silicon planes. The heat is transported to a condensers mounted onto the heat pipe radiators. The liquid is transported back to the evaporator by means of a mechanical pump.

The heat producing elements, the tracker front-end hybrid electronics are situated at the periphery of the tracker silicon planes and are located inside the cryogenic magnet. A total of 144 Watt is produced at 192 locations and an additional 6-10 Watt cooling capacity is required for additional electronics and a Star Tracker, which is also attached to the loop. The temperature requirements for the silicon waver and the hybrid front-end electronics are:

Silicon wafer thermal requirements	**Hybrid circuit thermal requirements**
Operating temperature: -10˚C / +25˚C	Operating temperature: -10˚C / +25˚C
Survival temperature: -20˚C / +40˚C	Survival temperature: -20˚C / +40˚C
Temperature stability: 3˚C per orbit	Temperature stability: 3˚C per orbit
Maximum allowed gradient between any silicon: 10.0˚C	
Dissipated heat: 2.0 W EOL	Dissipated heat: 144 W total (±10%) 0.75 W per hybrid pair (S=0.47 W, K=0.28 W)

The thermal design challenges of the TTCS for ASM-02 are:

- Compatibility with the existing Tracker Hardware.
- Limited volume.
- Multiple and widely distributed heat inputs up to 160 W.
- Minimal temperature gradients of less then 1^{o}C
- Low mass budget < 72.9 kg, low power budget < 80 watt.
- High reliability i.e. fully redundant system design.
- Two radiators thermally out of phase.

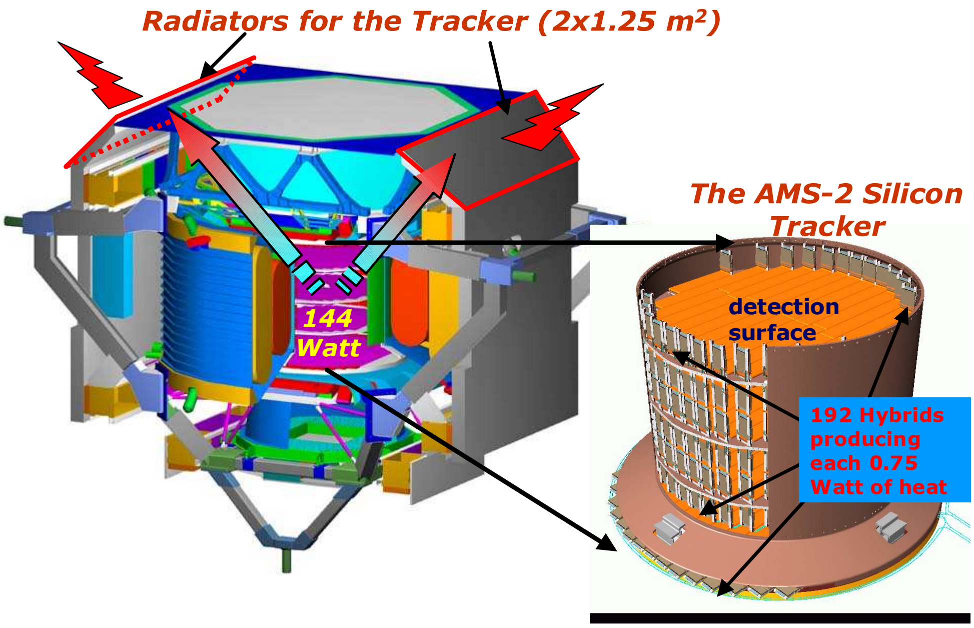


Figure 2-1: AMS-02 Silicon Tracker Schematic

2.3 TTCS loop lay-out

The main functionality of the TTCS loop is to transport heat dissipated by the tracker electronics to radiators that radiate the heat to deep space. For reliability reasons, two redundant loops will be implemented. In Figure 2-2, the layout of the primary TTCS-loop is given. The secondary loop is a hydrodynamic complete independent of the first one but has the same layout. By following the loop routing in 2-1 and 2-2 the loop operation is explained. At the pre-heaters the working fluid temperature is lifted to the saturation temperature. The working fluid enters the evaporator with a quality slightly above zero, ensuring a uniform temperature along the complete evaporator. Due to the widely distributed front-end electronics the evaporator consists of two parallel branches collecting the heat at the bottom and top side of the Tracker planes. At an overall mass flow of 2 g/s the mean quality at the outlet of the evaporators is approximately 30%.

The two-phase flow of both branches is mixed and led through the heat exchanger where heat is exchanged with the incoming subcooled liquid. Behind the heat exchanger the two-phase line (red) is split. One branch leads to the condensers at the RAM heat pipe radiator and the other is lead to the condensers at the wake heat pipe radiator. At the radiators the heat is rejected to space. After the mixing point of the two radiator branches, the sub-cooled fluid passes the accumulator. By controlling the accumulator temperature the evaporator set-point temperature is controlled by Peltier elements (cooling) and heaters. The set point can be varied to avoid extreme sub-cooling or operation with liquid temperatures just below saturation at the inlet of the pump. A distinct amount of sub-cooling is required to avoid cavitation at the pump.

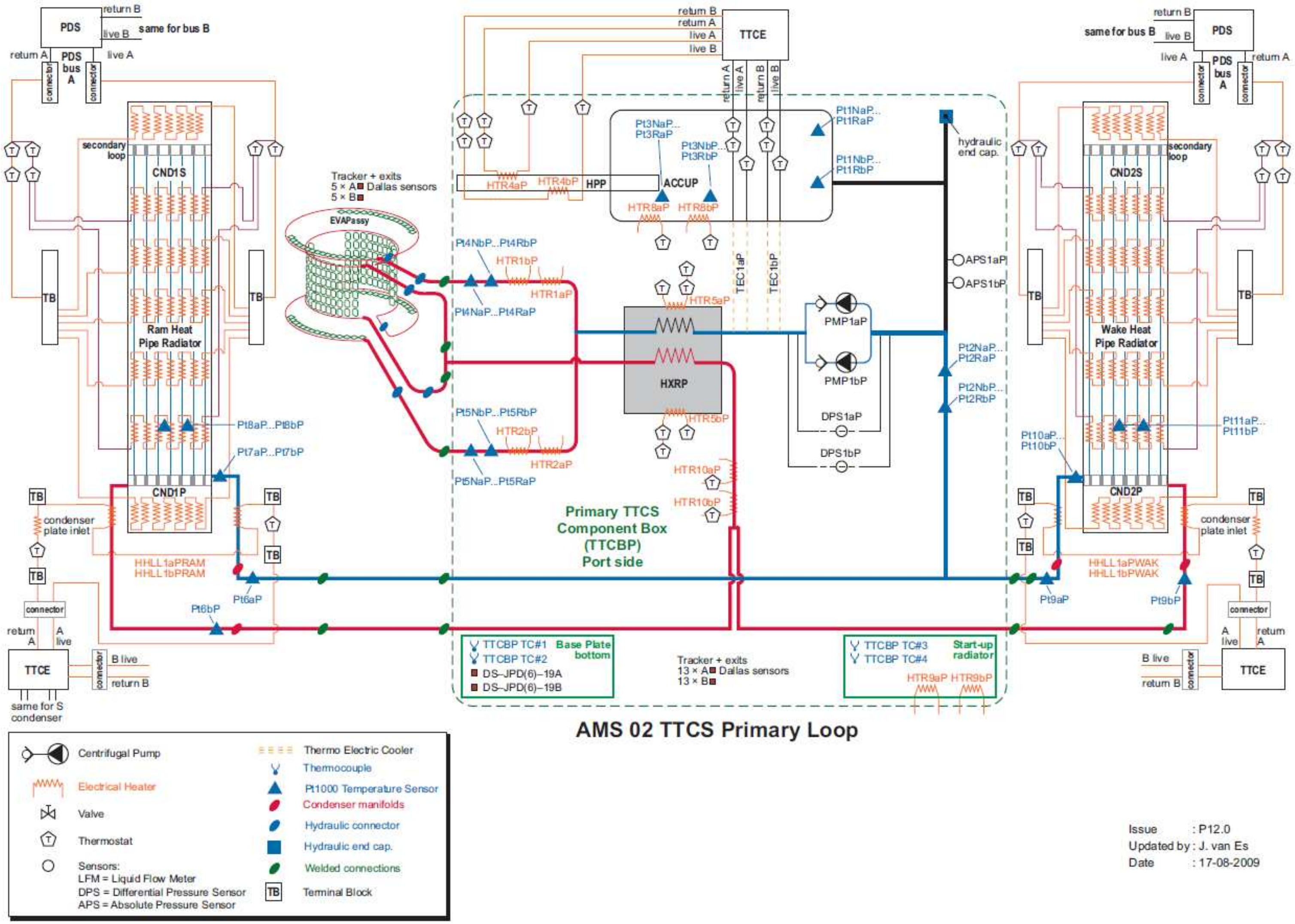


Figure 2-2: Schematic of the Tracker Thermal Control System Primary Loop

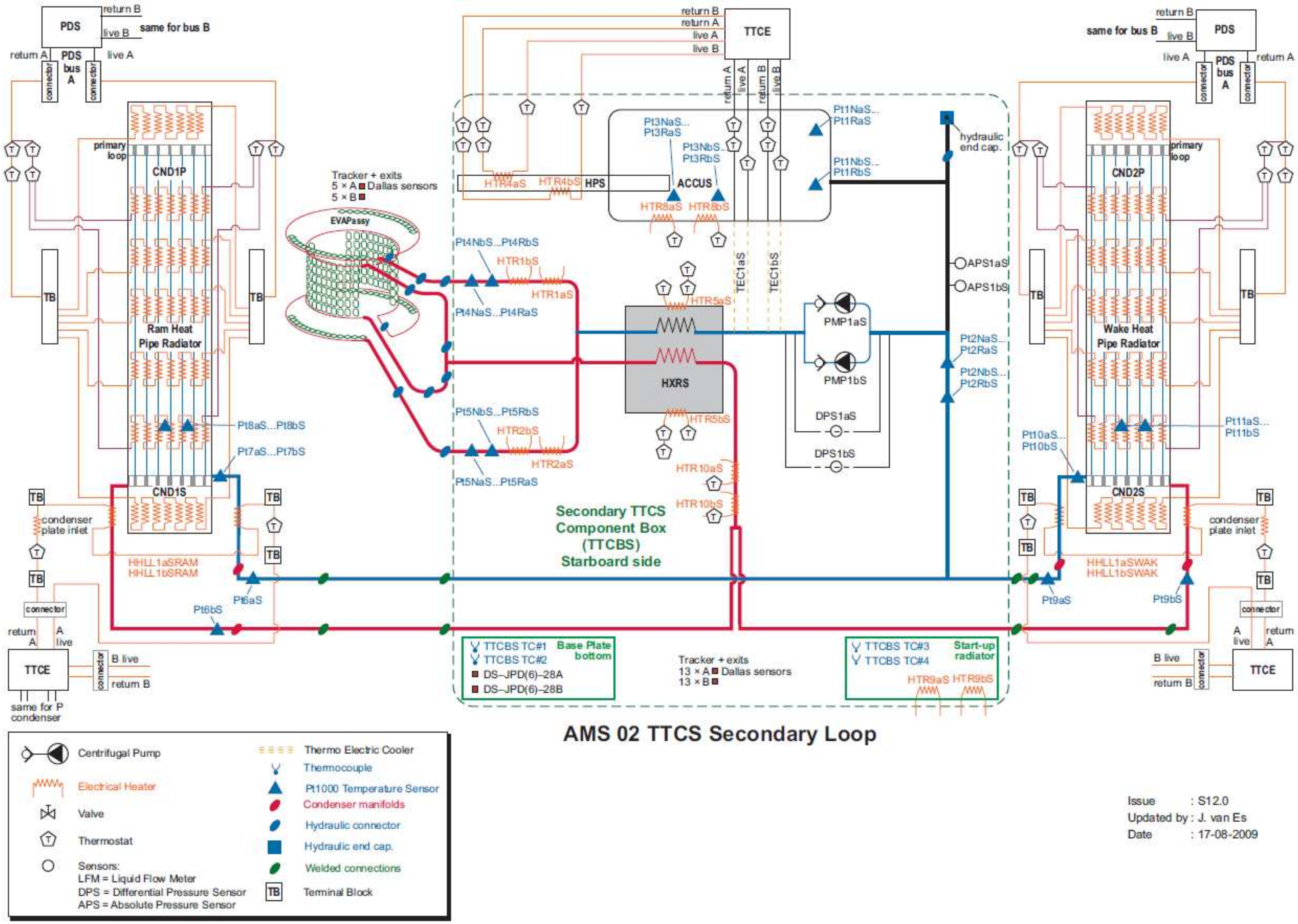


Figure 2-3: Schematic of the Secondary Loop

Behind the pump the sub-cooled fluid is warmed up in the heat exchanger before it enters again the pre-heater section.

2.4 Principal functionality of the components

Component	Function
Pump	Transport the fluid through the loop
Accumulator	Regulate the evaporator temperature in the tracker Account for the expansion of the working fluid
Accumulator Peltier elements	Regulate evaporation set-point in all operation modes (cooling)
Accumulator heaters	Regulate evaporation set-point in all operation modes (heating) Emergency accumulator heat-up in case liquid line temperature approaches saturation temperature (to avoid cavitation in pump)
Heat Exchanger	Exchange heat between hot evaporator outlet and cold evaporator inlet. Reduction of pre-heater power
Evaporator	Collect heat at the tracker electronics. The evaporation process provides the temperature stability required.
Condensers	Remove the heat from the working fluid to the radiators. The condensing process makes the heat transfer effective.
Absolute Pressure Sensors	Monitor the absolute pressure inside the loop
Differential Pressure Sensor	Monitor pump pressure head
Pre-heaters	Heat evaporator liquid inlet to saturation point
Start-up heaters	Additional heater for cold start-up (off during nominal operation)
Cold Orbit heater	Additional heater to keep the condenser temperature above CO2 freezing temperature (-55 ºC) during cold orbits
Liquid line health heaters	Heaters to defrost the condenser inlet and outlet lines after an AMS02 power down
Dallas Temperature Sensors	Monitor temperatures TTCS temperatures
Pt1000 Temperature Sensors	Control accumulator temperature Control pre-heater on/off Monitor cold temperatures on radiator and liquid lines

Table 2-1: Functional design of the loop

3 Specifications and Requirements

3.1 System requirements

3.1.1 Functional Performance

The main objective of the TTCS system is to keep the Tracker electronics within the required temperature limits. It transports the dissipated heat from the Tracker electronics to two dedicated radiators. One on RAM-side and one on the WAKE-side of AMS. Both radiators are thermally out of phase, meaning that the orbital load is either on WAKE or on RAM, but not on both radiators at the same time.

3.1.2 Design temperatures

The temperature limits for the silicon wafer and for the hybrid circuits are summarised in the next subsections.

3.1.2.1 Tracker Electronics temperature requirements

Silicon wafer thermal requirements	Hybrid circuit thermal requirements
Operating temperature: -10˚C / +25˚C	Operating temperature: -10˚C / +25˚C
Survival temperature: -20˚C / +40˚C	Survival temperature: -20˚C / +40˚C
Temperature stability: 3˚C per orbit	Temperature stability: 3˚C per orbit
Maximum allowed gradient between any silicon: 10.0˚C	
Dissipated heat: 2.0 W EOL	Dissipated heat: 144 W total (±10%) 0.75 W per hybrid pair (S=0.47 W, K=0.28 W)

Table 3-1: Tracker Electronic Temperature Ranges

The Tracker electronics are located near the Tracker silicon wafer plates.

3.1.2.2 TTCS Electronics temperature requirements

TTCE thermal requirements in TTCE box
Operating temperature: -20˚C / +55˚C
Survival temperature: -40˚C / +85˚C

Table 3-2: TTCE Electronic Temperature Ranges

The TTCE electronics box is located at the Wake-side on the main radiator.

TTCE thermal requirements for electronic parts in TTCS-P and TTCS-S box
Operating temperature: -20˚C / +55˚C
Survival temperature: -40˚C / +80˚C

Table 3-3: TTCS Electronic Temperature Ranges
(08-09-2009 consistent with pump electronics reqs)

3.1.2.3 TTCS Fluid temperature ranges

TTCS Fluid temperature ranges
Operating Temperature loop (set-point): -20˚C / +25˚C
Survival temperature:
-120 ˚C / +65˚C
Start-up temperature:
-40 ˚C / + 30˚C (accumulator start-up temperature)

Table 3-4: TTCS Fluid Temperature Ranges (08-09-2009)

3.1.3 Redundancy concept and requirements

The AMS overall philosophy is **the avoidance of any single-point of failure**. The TTCS subsystem is therefore completely redundant. **Two complete independent loops are fully equipped to fulfil the thermal control task** for the Tracker electronics. In principle one subsystem is hot and the other cold (i.e. the subsystem will not be operating at the same time)

The philosophy is further that also **no single-point of failure is present in one of the two systems**. All critical mechanical components in the separate loops are therefore also redundant. A list of redundant components is given in Table 3-.

Component	**Redundancy per loop (# per loop)**
Pump	2
Accumulator	1
Accumulator Peltier elements	2
Accumulator heaters	2
Heat Exchanger	1
Evaporator	1
Condensers	1
Absolute Pressure Sensors	2
Differential Pressure Sensor	2
Pre-heaters	2
Start-up heaters	2
Dallas Temperature Sensors	2
Pt1000 Temperature Sensors	3 or 2**
Cold orbit heaters	2
Liquid line health heaters	2
Tracker radiator heaters***	2 (connected to PDS A-side and to PDS B-side)
TTCE including:	**2**
TTEP	2
TTEC	2
TTPP (A/B) A and B both on one board	2 (but one mechanical connector) No control-Pt1000's are connected to this board.
TTBP (A/B) A and B both on one board	2
Redundancy interfacing systems	
CAN-bus	2
JMDC	4

Table 3-5: Component redundancy
*** The Pt1000's used for control are triple redundant the monitoring Pt1000's are redundant.*
****The survival heaters are not part of the TTCS-system but are incorporated for completeness.*

The same holds for the complete chain of components and electronics. The TTCE electronics are also completely redundant and divided in an A and B electronics block. A block diagram is shown in Figure 3-1.

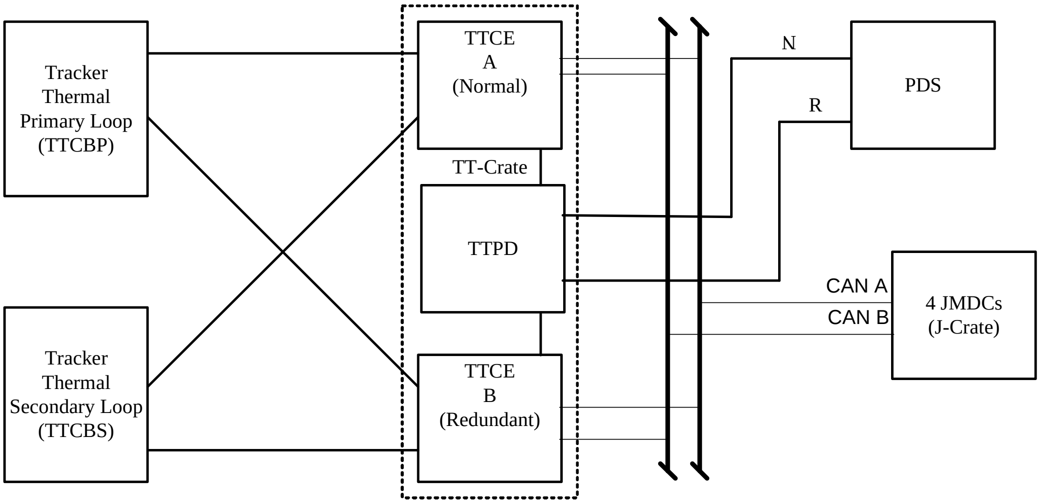


Figure 3-1: TTCS Electronics Block Diagram

From Figure 2-2 and Table 3- it is shown that all electrical components are redundant in as well the primary as the secondary loop. One of each component is attached to electronics A and the redundant component is connected to electronics B (in the components list, indicated with a and b (see RD-30).

To allow for the maximum use of all critical components it is decided to be able to operate A and B electronics simultaneously.

3.1.4 Power budget

The power budget allocated to the TTCS system during operation is 134 Watt.

TTCS Power budget	
Allocated power budget (AMS) nominal	134 Watt
Average actual power (estimated)	70 Watt
Nominal total one loop (28 V)	126 Watt
Nominal total one loop cold orbit (28V)	212 Watt
Nominal total one loop start-up (28 V)	202 Watt
Tracker radiator heaters during start-up (120 V)	352 Watt
Transition from start-up to Tracker on (28 V)	263 Watt

Table 3-2: TTCS Power budget

The allocated power budget is a number representing the mean power to be delivered to TTCS during operation.

			Primary loop				Power Primary Loop			Average Power		Absolute Total Power
Type	Voltage	Power	Units				Primary	Primary in cold orbit	Primary Loop Start-up	Primary Loop		Primary Loop
		Single	Nom	Cold	Start-up	Abs Total	Nom Total	Nom total A	Nom total A	Avg. Total	Remarks	Abs. Total A
	[V]	[W]	[]	[]	[]	[]	(1) [W]	(6) [W]	[W]	(4) [W]	No design values	[W]
							125.66	212.86	202.86	69.92		262.86
PDT 5059	28	15	1	1	1	1	15.00	15.00	15.00	7.5	1 pump 50% active	15.00
wire heater	28	8.9	2	2	2	2	17.80	17.80	17.80	17.80	100 % active (on/off)	17.80
wire heater	28	60		1		1		60.00			not active	60.00
wire heater	28	50			1	1			50.00		not active	50.00
	28	42.9	1	1	1	1	42.90	42.90	42.90	17.16	40% active	42.90
wire heater	28	37.5	1	1	1	1	37.50	37.50	37.50	15	40% active	37.50
	28	0.2	1	1	1	1	0.20	0.20	0.20	0.20		0.20
	28	0.2	1	1	1	1	0.20	0.20	0.20	0.20		0.20
wire heater	28	13.6		2	2	2		27.20	27.20		not active	27.20
DS1820	5	0.003									not active	
PTFA Pt-1000	5	0.003	15	15	15	15	0.05	0.05	0.05	0.05		0.05
PTFA Pt-1000	5	0.003	6	6	6	6	0.02	0.02	0.02	0.02		0.02
S&A	28	12	1	1	1	1	12.00	12.00	12.00	12.00		12.00

Table 3-3: Power budget (Powerbudget11_09_09_V01.xls)

Explanation of the power budget table:

Primary nominal:	Power when nominal actuators of primary loop are 100% active
Primary Cold orbit:	Power during cold orbit with additional heaters 100% active
Primary Start-up	Power required during start-up with additional heaters 100% active
Primary Absolute total:	Power when all actuators of primary loop are 100% active
Average power:	Average power during nominal operation (one loop) with only nominal actuators partly active

*Remark 1: The average power is a value requested by AMS-consortium but not an official NLR number. For NLR lower numbers are only acceptable as design value when the electronics is designed such that simultaneous use is excluded. Although it is unlikely that all components request power at once. NLR considers the absolute total power as design value.

The Secondary Loop is an exact copy of the Primary Loop the power budget is therefore the same.

3.1.5 Mass budget

The mass budget distribution is given in Table 3-4. The overall estimated mass budget is 69.9 kg. This is the below the initial allocated budget of 72.9 kg. The mass breakdown is shown below and is based on 95% mass measurements.

		Primary Loop	Secondary Loop	TTCS Complete	Percentage of total TTCS mass
Description	# Overall Number (P+S)	Estimate 02-02-2009 (kg)	Estimate 02-02-2009 (kg)	Estimate 02-02-2009 (kg)	
Centrifugal Pump	4	3.15	3.22	6.37	9.11
Preheaters	8	0.95	0.95	1.90	2.72
Start-up heaters	4	0.02	0.02	0.04	0.06
Cold orbit heater	2	0.35	0.35	0.69	0.99
Absolute pressure sensors	4	0.31	0.31	0.62	0.89
Differential pressure sensors	4	0.59	0.59	1.18	1.69
Wire heaters condenser lines	8	0.50	0.50	1.00	1.43
Temperature sensors Dallas	128	0.95	0.95	1.90	2.72
Temperature sensors PT1000	120	1.75	1.75	3.50	5.01
Accumulator (including saddle, peltiers etc)	2	3.81	3.81	7.61	10.88
Heat Exchanger	2	1.74	1.74	3.48	4.98
Condenser	4	9.00	9.00	18.00	25.75
Fluid	2 loops	0.93	0.93	1.86	2.65
Tubing	2	0.51	0.42	0.93	1.32
Tube connectors	80	0.60	0.60	1.20	1.72
TTCS box	2	4.90	4.90	9.80	14.02
Mounting frames, brackets bolts	2	3.80	3.80	7.60	10.87
Thermostats (box)	20	0.30	0.30	0.60	0.86
					0.00
MLI	1	0.20	0.20	0.40	0.57
Cable harness TTCB's	2	0.50	0.50	1.00	1.43
Contingency	1		0.00	0.23	0.33
Total current budget:		34.9	34.8	**69.9**	100.0
Original budget		Primary Box	Secondary Box	72.9	
		19.92	19.98	3.0	

Table 3-4:TTCS Mass Budget

3.1.6 Electrical interfaces

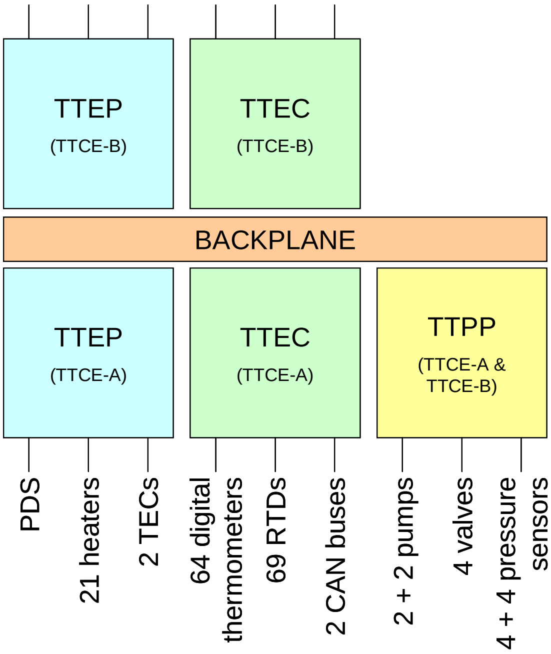


Figure 3-2: TTCE Interface block schematic

The main interfaces are show in Figure 3-2. It must be remarked that the valve control electronics although present on the TTPP are not used as the valves are deleted from the TTCS design. Also the FPGA does not suppport the valve controls on the TTPP. All details on the electrical interfaces are summarised in the AMS02 TTCE Interface Control Document RD-5.

3.1.7 Proof/Burst Pressure

In a two-phase system the pressure, temperature and density are interrelated. The maximum design conditions are based on the notion that the entire system pressure should not exceed 160 bar pressure (Maximum Design Pressure MDP) and a maximum temperature (average over the entire system) of 65 °C. The maximum allowable fill rate (system density) is then directly determined from the Mollier diagram, seen in ***Figure 3-3***, as the intersection between the blue line (constant temperature (65 °C) line) and the horizontal line of constant pressure.

In Figure 3-3 the Mollier diagram is seen for CO_2. The intersection of the T= 65 °C curve (blue line) with the ρ = 592.39 [kg/m^3] (red line) occurs at a pressure of 160 Bars:

- Max Design Pressure 160 [Bar]
- Max Design Temperature 65 [°C]
- Max Design Density 592.39 [kg/m^3] (=mass/volume)

The above pressure, density and temperature relations are based on the notion of constant temperature over the entire system. If the temperature of a part of the loop is below the 65 °C the required volume to contain the CO_2 @ 160 Bars is smaller than the actual loop volume. This implies that the other parts of the loop can get warmer without exceeding the 160 Bars in pressure. This is approach is used for the safety analysis (RD-6).

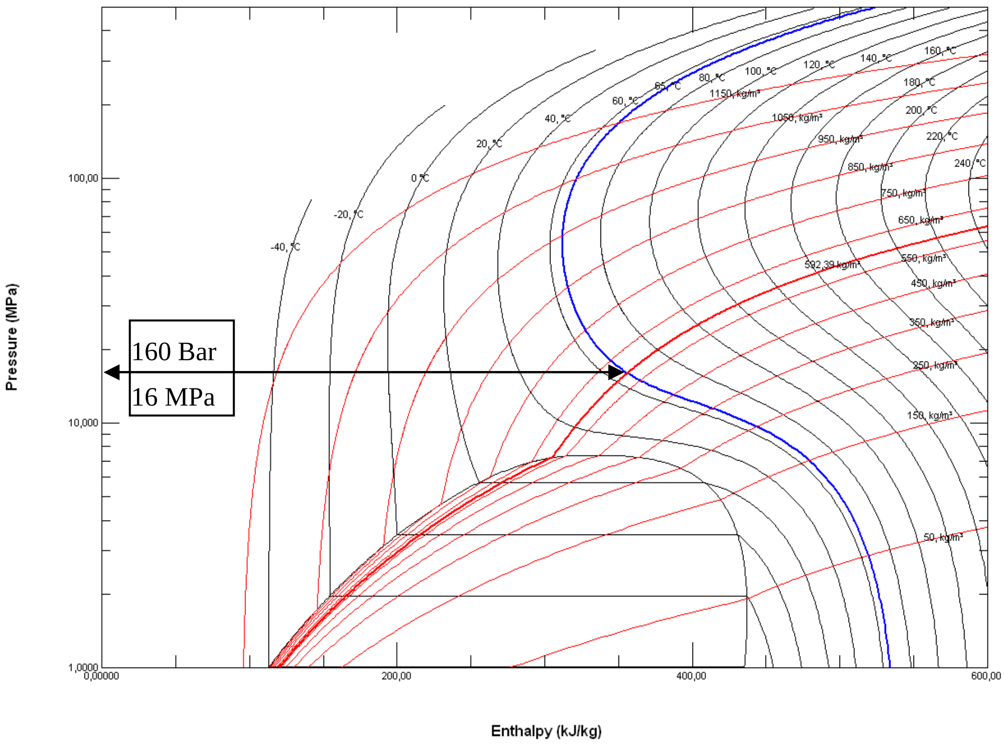


Figure 3-3: Mollier diagram

Although different maximum temperatures are used for different parts of the loop the MDP in a two-phase is for all components the same. The design proof pressures are summarised in the below table and are based on the general design rules shown in Appendix II. For the condensers a special pressure regime is valid (RD-7). The condensers are located on the Tracker radiators. In case of an AMS02 power down these radiators can decrease to temperature well below the CO_2 freezing temperature (-55°C). Therefore the condensers are designed such that they can withstand the highest pressure build up during thawing (3,000 bar) with still frozen inlets and outlets.

TTCS design pressures			
TTCS components	MDP [bar]	Proof pressure [bar]	Burst pressure [bar]
Evaporator tubing	160	240	640
Tubing in TTCS-P-box & TTCS-S box	160	240	640
TTCS-components - pumps - APS - DPS - Accumulator - Condenser manifolds - Hydraulic connectors	160	240	400
Condenser	3,000	6,000	12,000

Table 3-5: TTCS MDP, proof and burst pressures

It is experimentally verified (RD-7) that the pressure build-up in the condenser design during thawing perfectly follows the melting line (see Figure 3-4). The highest pressure is based on the maximum Tracker radiator temperature after AMS-02 power down. The condenser design is also tested for proof and burst. The verified burst pressure (10,000 bar) is agreed with NASA safety and uses a safety factor of 3.33.

3.1.8 Rupture criteria

All components shall be designed to leak before burst criteria. During the verification it was shown that all components don’t show leaks at burst pressures.

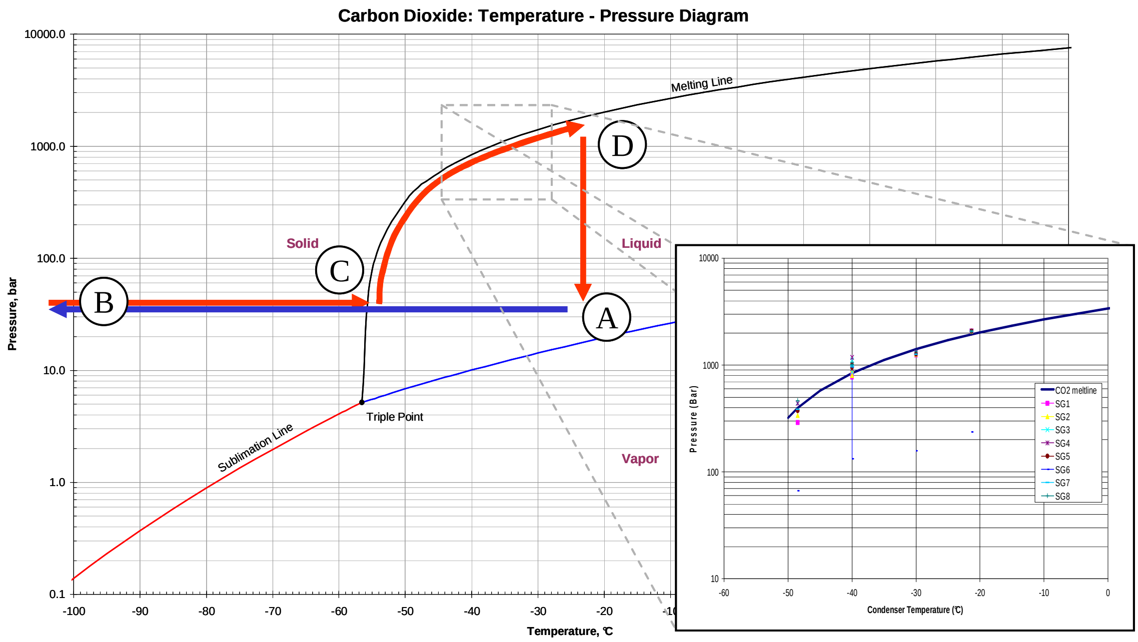


Figure 3-4: Maximum design pressure plotted along CO_2 melt line

3.1.9 Leak tightness requirements and sealing

The overall leak tightness is based on a CO_2 mass loss of 30 g in 5.5 years based on average operating pressures on earth and in space. The required helium leak rate equivalent is calculated to verify the leak tightness and subdivided in leak budgets of TTCS components and subassemblies (RD-9). The leak budgets are shown below per component, subassemblies and TTCS-system.

Complete TTCS		**Maximum allowed He leak rate (vacuum method)**
Complete TTCS		**1×10^{-7} mbar.l/s**

Table 3-6: Maximum allowed He leak rate, complete integrated TTCS

Integrated parts		**Maximum allowed He leak rate (vacuum method)**
Component box		**4×10^{-8} mbar.l/s**
Condensers + manifolds + feed/return lines		**3×10^{-8} mbar.l/s**
Evaporator + feed/return lines + hydraulic connectors		**3×10^{-8} mbar.l/s**
Total		

Table 3-7: Maximum allowed He leak rate, 'integrated parts' level

The requirements for the assemblies are less strict then for the individual components. This is done for practical reasons in view of the number of test connectors necessary during verification.

Component	**Item Code**	**Maximum allowed He leak rate (vacuum method)**
Pump	PMP1aP	$1x10^{-9}$ mbar.l/s
Pump	PMP1bP	$1x10^{-9}$ mbar.l/s
Diff. pressure sensor	DPS1aP	$1x10^{-9}$ mbar.l/s
Diff. pressure sensor	DPS1bP	$1x10^{-9}$ mbar.l/s
Abs. pressure sensor	APS1aP	$1x10^{-9}$ mbar.l/s
Abs. pressure sensor	APS1bP	$1x10^{-9}$ mbar.l/s
Accumulator	AccuP	$1x10^{-9}$ mbar.l/s
Heat Exchanger	HXRP	$1x10^{-9}$ mbar.l/s
EvapTop (without connectors)		$1x10^{-9}$ mbar.l/s
EvapBot (without connectors)		$1x10^{-9}$ mbar.l/s
SUBTOTAL		**$1.0x10^{-8}$ mbar.l/s**
All hydraulic connectors		$2x10^{-8}$ mbar.l/s
All orbital welds		$2x10^{-8}$ mbar.l/s
Condenser, incl manifolds	CND1P	$2x10^{-8}$ mbar.l/s
Condenser, incl manifolds	CND2P	$2x10^{-8}$ mbar.l/s
TOTAL		**$9.0x10^{-8}$ mbar.l/s**

Table 3-8: Maximum allowed He leak rate, component level

The verification is performed with the Helium vacuum test method as this is the best way to quantify leaks. An additional only qualitative check is performed with the Helium sniffer method on the TTCS working pressure. This is to detect leaks only arising at high pressures. Prime suspects are the hydraulic connectors used in the design. The verification of subassemblies so far (TTCB's and condensers) showed vacuum method leak rate values better then the requirements.

Pinching and closure

The system shall be closed with pinch and a second closure. Welding is not allowed to not damage the connected Tracker Electronics. The total closure shall have the same leak tightness as hydraulic connectors used in the loop. The verification of the last closure (pinch and connector) of the system will be performed with a CO_2 mass spectrometer as verification with any Helium test method is not possible. The schematic set-up is shown in Figure 3-5.

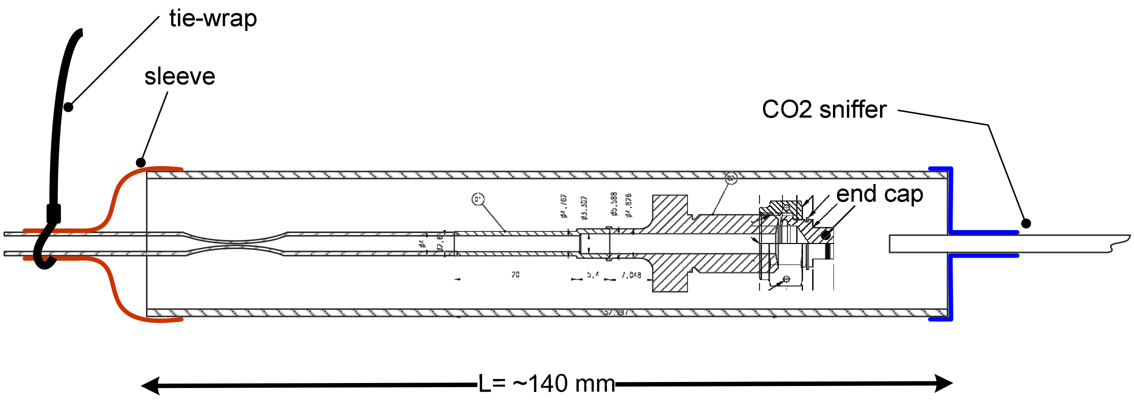


Figure 3-5: Schematic leak detection set-up for pinch and closure

3.1.10 Cleanliness

The TTCS-loop element and the TTCS components shall not contaminate the system working fluid.

Metallic particles are not allowed.

The maximum number of non-metallic particles in a 100 ml sample shall be as follows and is equivalent to MIL-STD-1246 C class 100:

- > 100µm none
- 100 µm 5 max
- 50 µm 50 max
- 25 µm 200 max
- 10 µm 1200 max
- 5 µm no limit

The cleanliness of components shall be verified by detection. Tubes and connectors shall be procured clean and kept clean by working according to procedures.

3.1.11 Orientation

System orientation

The TTCS-system shall be able to operate during ground testing. Loop split point and pre-heaters shall be located such that no phase separation can occur during ground testing.

Pump orientation

The pump shall be dimensioned such that the additional gravitational pressure head can be performed.

Remark: Due to the limited amount of CO_2 in the loop and the small diameter size, is the gravitational pressure head is negligible compared to the overall pressure head.

Accumulator orientation

The accumulator shall be able to provide full operational performance during ground testing. The accumulator shall therefore operate in all orientations in ground test conditions.

3.1.12 Vacuum

The TTCS shall be able to operate in high vacuum ($1*10^{-6}$ mbar). Materials should no degrade at vacuum conditions.

3.1.13 Compatibility

All TTCS materials shall be compatible with the working fluid Carbon Dioxide (CO_2) and Isopropyl Alcohol (IPA) which will be used as cleaning material.

3.2 Environmental Requirements

The TTCS is part of the AMS02-mission. Therefore the TTCS has to be able to survive all environmental conditions during this mission.

The mission is subdivided in the following mission phases:

- Storage (TTCS non-operating)
- Ground testing conditions (TTCS operating/functional check)
- Launch conditions (TTCS non-operating)
- Shuttle bay (TTCS non-operating)
- Transfer from shuttle to ISS truss (TTCS non-operating)
- ISS-truss (TTCS start-up, TTCS-operating, and TTCS non-operating)

During all mission phases the TTCS must survive the environmental conditions. The environmental conditions comprise:

- Thermal environment requirements
- Vibration and shock requirements
- EMC and EMI requirements
- Radiation requirements

In the following sections the environmental conditions are detailed. For the thermal environment the conditions are detailed per orbit and per mission phase.
For all other environmental requirements the worst case requirements are given. When appropriate standards are/will be used a reference to the to be used standards is given.

3.3 Thermal Environmental Requirements/Orbital data

The TTCS is part of the AMS-experiment and will be transported by the Space Shuttle to the International Space Station ISS. Main interface of the TTCS with the orbital environment are the Tracker radiators.
In this subsection first a summary is given of orbital data. Out of these conditions the worst case operational and non-operational conditions are selected and defined in separate subsections.

The extreme conditions are defined by the following:
<u>Extreme hot condition</u>

- Hottest environmental condition (highest TTCS radiator temperature(s))
    - Worst case optical properties (worst case α/ε combination)
        - high α (solar absorption)
        - low ε (IR emission coefficient)

- Largest solar/albedo/earth heat load
- Maximum possible power dissipation during hottest part of orbit

Extreme cold condition

- Coldest environmental condition (lowest TTCS radiator temperature(s))
  - Worst case optical properties (worst case α/ε combination)
    - low α (solar absorption)
    - high ε (IR emission coefficient)
  - Lowest solar/albedo/earth heat load
  - Lowest possible power dissipation during coldest part of orbit

3.3.1 Summary of all orbital thermal data

In Figure 3-6 a schematic of two extreme space station orbits is presented. Main change in orbital data is due to the change in beta angle (angle between the ISS orbital plane and the sun vector (earth centre to sun).

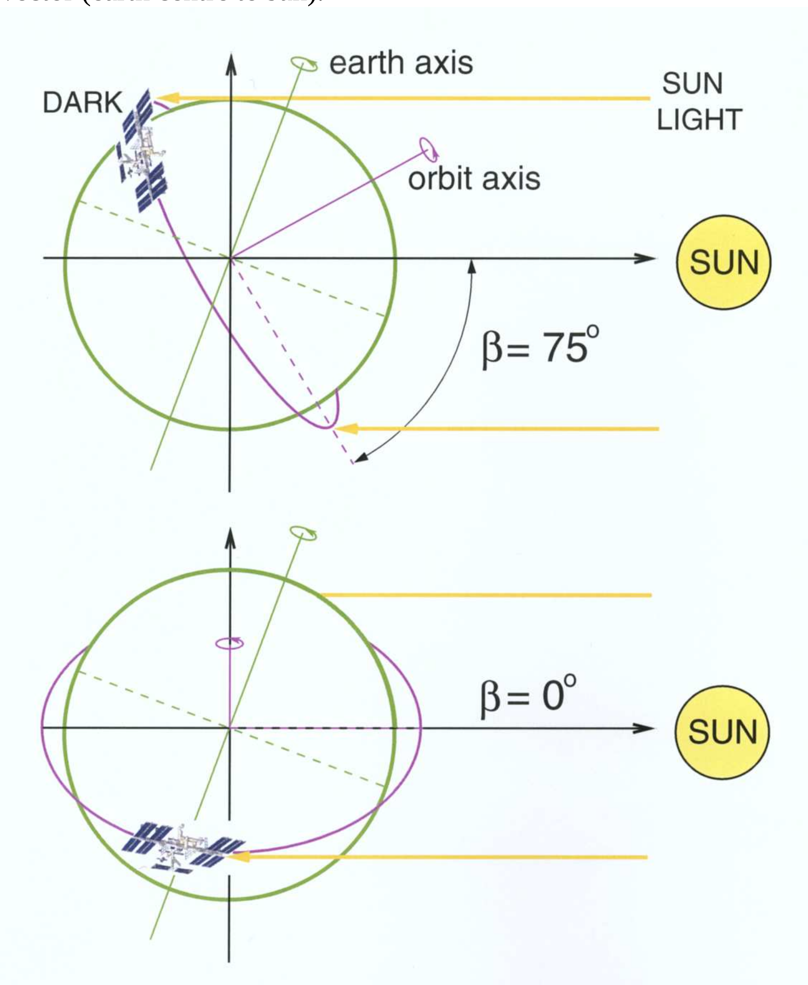


Figure 3-6: ISS orbit extremes

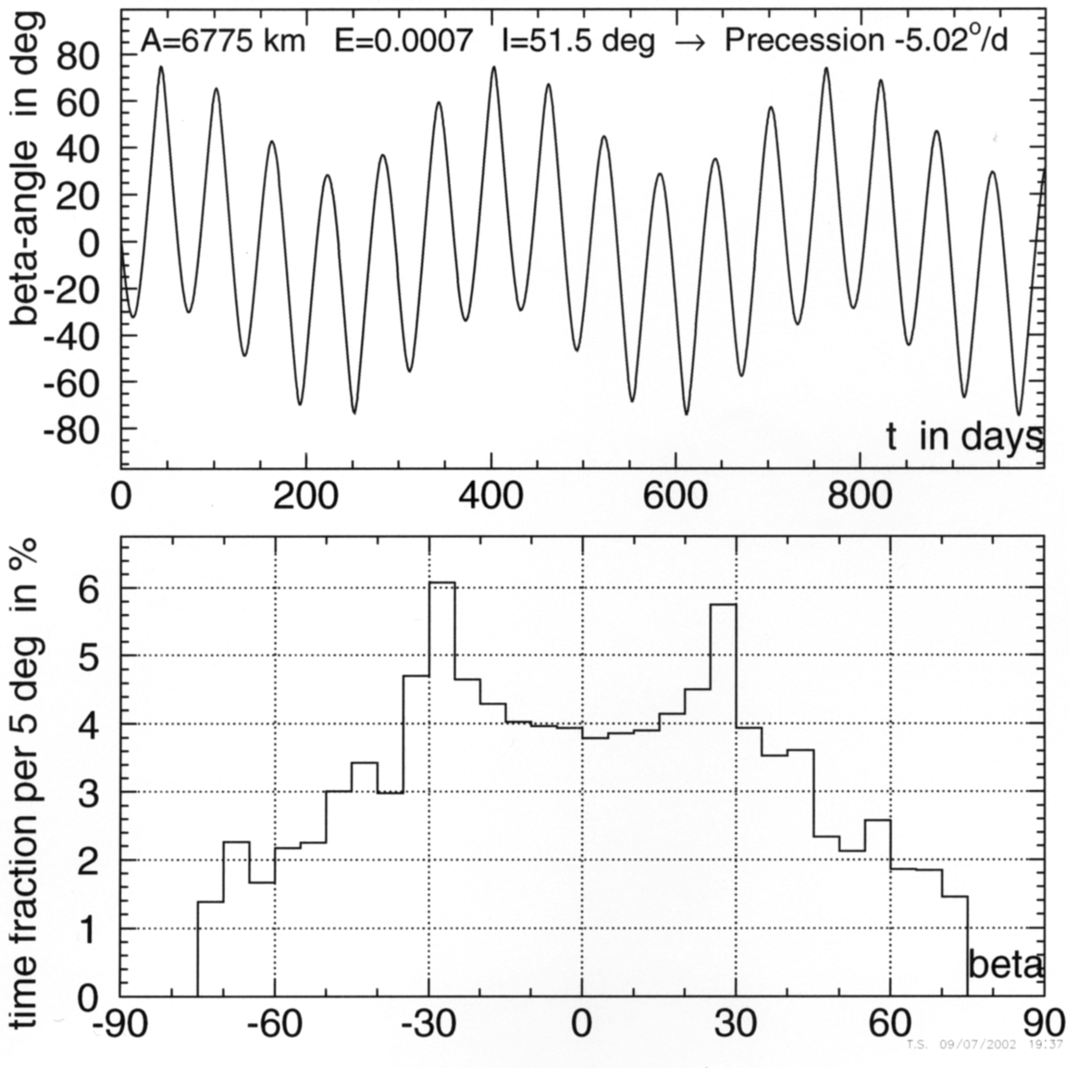
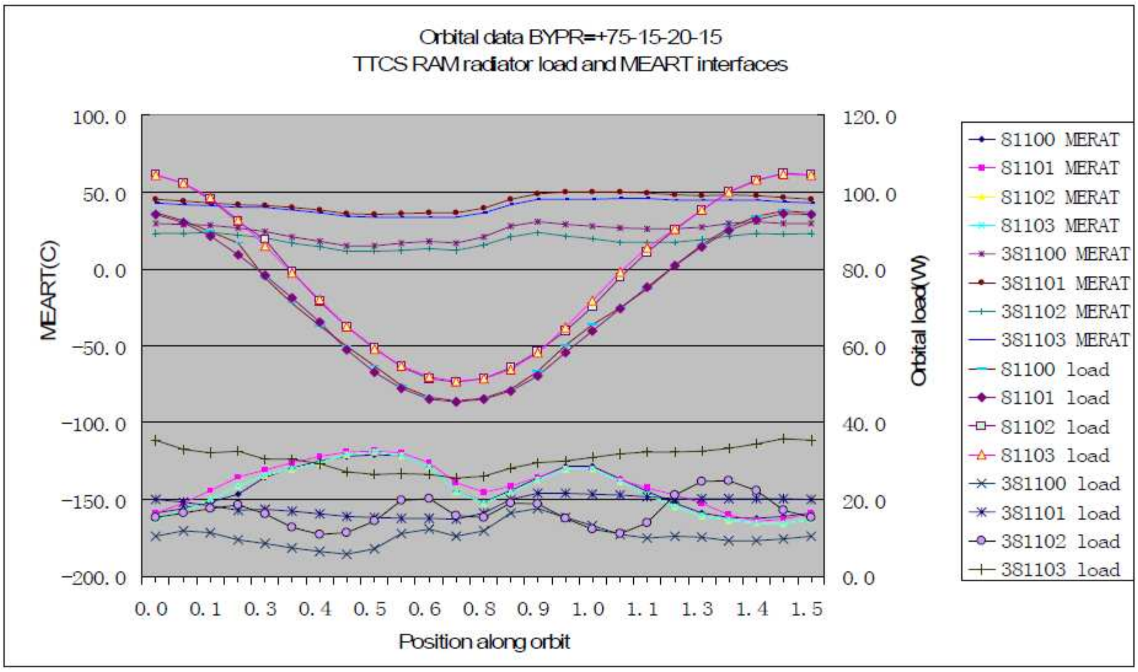


Figure 3-7: Relative time share of ISS orbits

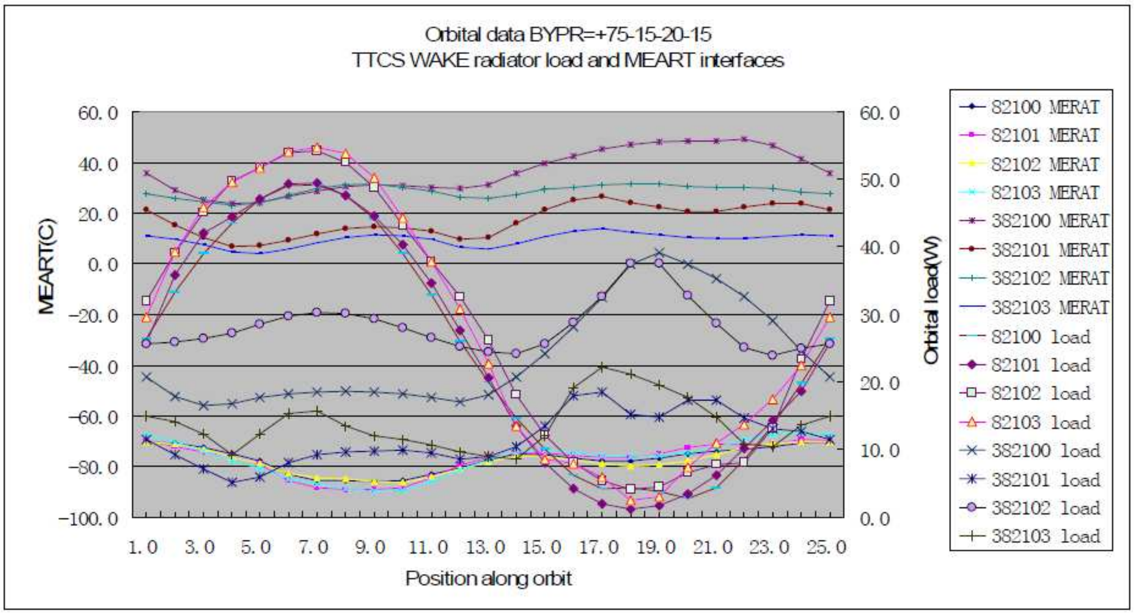
In Figure 3-7 the relative time-share of the different orbits is shown in a histogram. Beta angles of +75 and –75 are scarce and most time AMS (on ISS) will view orbits around beta-angles of –30 and +30. In Figure 3-8 typical orbital interface data is presented. The full orbital data consists off:

1. MERAT temperatures of the RAM and Wake Tracker radiators.
2. View temperatures at the back side of the radiator
3. Orbital loads (sun solar earth) on the RAM and Wake Tracker radiators
4. Orbital loads at the back (inside) of the RAM and Wake radiators
5. Orbital loads on the TTCB's
6. USS I/F temperatures
7. Tracker I/F temperatures

RAM radiator



WAKE radiator



MERAT and orbital load of TTCB

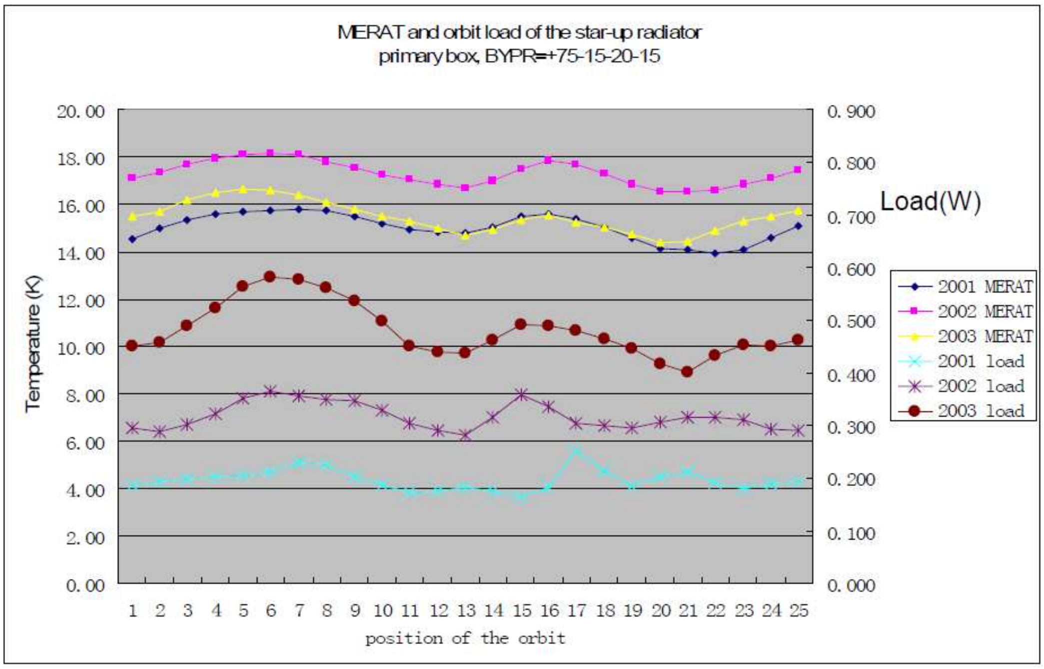


Figure 3-8: Typical orbital data for hot orbit Beta+75-15-20-15 (all TTCS orbital data is found in RD-13)

The figure shows the MERAT temperatures and orbital loads on the RAM and WAKE Tracker radiator and the TTCB-P start-up radiator. The MERAT temperatures are the effective temperatures of the radiator surroundings, excluding the orbital heat load. Each Tracker radiator is divided in four parts and for each part an MERAT temperature is given. The nodal distribution for the RAM-radiator is shown in Figure 3-9.

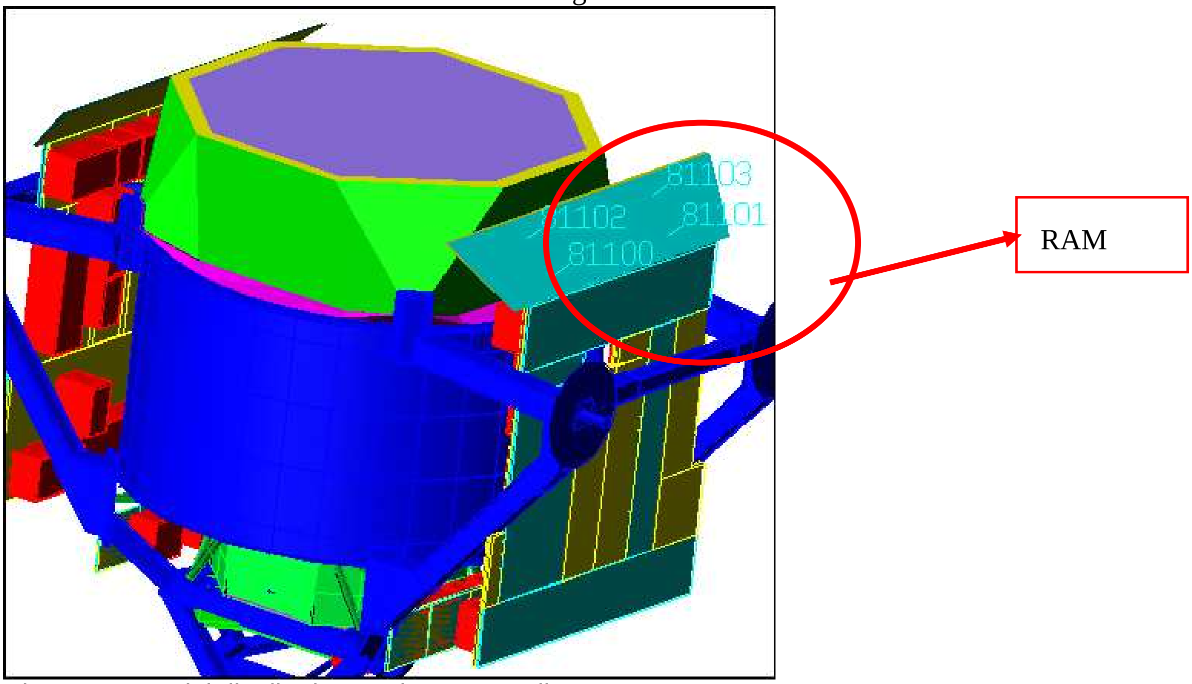


Figure 3-9: Nodal distribution on the RAM-radiator

Each node has a rectangular trapezoidal shape, whose dimensions are:

- For the lower, smaller nodes: 0.29 m2
- For the upper, bigger nodes: 0.32 m2

In Appendix III the orbital data for 10 representative orbits is given. These interface data are calculated by CGS (Italy) based orbital calculation of AMS and ISS.

3.3.2 Radiator temperature calculation

The above-presented orbital data are used to calculate the temperatures of the radiator. In non-operating cases the heat exchange with the environment is small. Therefore the Tracker radiator environment temperatures are not influenced by the radiator heat exchange. However during operation the TTCS dumps 154 Watt in the environment, thereby heating the environment. The given orbital data are therefore too optimistic. To account for this mutual interference the radiator temperatures during operation have been calculated in co-operative effort between NLR and CGS. The sequence is shown in Figure 3-10. Experience has learned that after one full iteration the radiator temperatures converge and the solution is reliable to use for design.

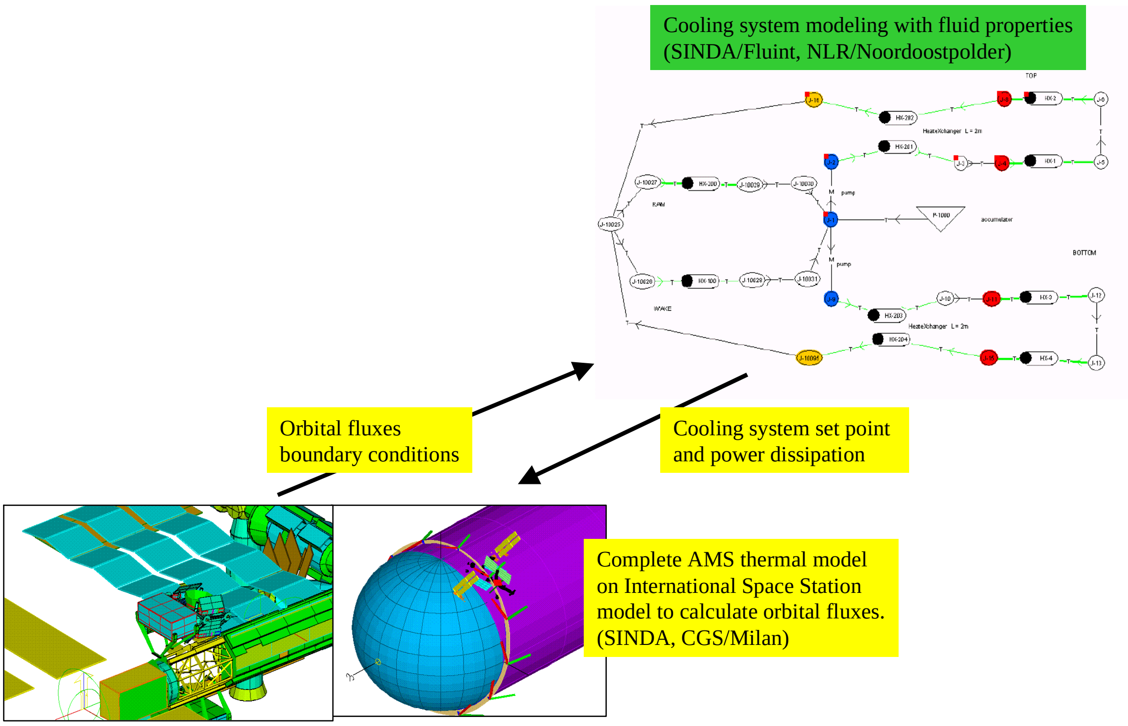


Figure 3-10: Calculation sequence to calculate Tracker radiator temperatures

3.3.3 Hot case operational

The TTCS hot case operational phase is defined as:

- Tracker heat load 144 Watt
- Star Tracker heat load 10 Watt
- TTCS Pump dissipation 15 Watt
- Hot orbit

For details on power dissipation see RD-12. An extensive survey on 259 attitude/beta angle combinations has been done to identify the hottest and coldest orbits. The results are presented in Appendix III. All orbital data can be found in RD-13.

The following orbits are defined as Tracker radiator hottest orbits:

- Beta+75-15-20-15
- Beta+75-15+00-15

Remark: A hot orbital indication in the AMS02 general interface data means a hot orbit for AMS02 overall. That does not automatically imply a hot orbit for the Tracker radiators.

Impact on system design

The hot case operational is used to define the (minimum) set-point in hot cases.

3.3.4 Cold case operational

The TTCS cold case operational phase main active components are:

- Tracker heat load 144 Watt
- Star Tracker heat load 0 Watt
- TTCS Pump dissipation 10 Watt
- Cold orbit

For details of the power dissipation see RD-12. An extensive survey on 259 attitude/beta angle combinations has been done to identify the hottest and coldest orbits. The results are presented in Appendix III and in RD-13

The following orbits are defined as Tracker radiator coldest orbits:

- Beta-75_+15_0-15
- Beta-75_0_0-15
- Beta-75-15_0+15
- Beta+75+15+15+15

Impact on system design

The cold case operational is used to define size the cold orbit heater to avoid condenser freezing during cold orbits.

3.3.5 Cold case non-operational

The cold case non-operational is defined as:

- Tracker heat load 0 Watt
- Star Tracker heat load 0 Watt
- TTCS Pump cooling 0 Watt
- Health heaters (radiator, liquid lines) on
- Cold orbit

The following orbits are defined as Tracker radiator coldest orbits:

- Beta-75_+15_0-15
- Beta-75_0_0-15
- Beta-75-15_0+15
- Beta+75+15+15+15

<u>Impact on system design</u>

The cold case non-operational is important to perform the heater sizing of the health heaters on the Tracker radiators.

This case is also used to size the accumulator such that in cold conditions still fluid is present in the accumulator.

3.3.5.1 Freezing requirements

<u>Freezing problem explanation</u>

Freezing of (parts) the TTCS-loop can occur when the temperature drops below –55 °C. The freezing itself is not a problem. However during thawing it is possible that fluid CO_2 sections are created in between solid sections. By increasing temperatures this will induce high pressures (upto 3000 bar).The freezing temperature is only reached at and nearby the Tracker radiators. The only component involved in freezing is the condenser (see section **Error! Reference source not found.**). For other parts of the loop it is verified no temperatures below –55 °C are possible (RD-14).

For the freezing problem the following case is defined as cold case with AMS02 power down:

- Tracker heat load 0 Watt
- Star Tracker heat load 0 Watt
- TTCS Pump cooling 0 Watt
- Health heaters (radiator, liquid lines) off
- Cold orbit

The following orbits are defined as Tracker radiator coldest orbits.

- Beta-75_+15_0-15
- Beta-75_0_0-15
- Beta-75-15_0+15
- Beta+75+15+15+15

Impact on system design

The cold case non-operational is important to check the lowest Tracker radiator temperature. Important for heater, thermostats and temperature sensor specifications.

3.3.6 Hot case non-operational

The hot case non-operational is defined as:

- Tracker heat load 0 Watt
- Star Tracker heat load 0 Watt
- TTCS Pump cooling 0 Watt
- Health (survival) heaters working on thermostat set-point
- Hot orbit

The following orbits are defined as hottest orbits for the Tracker radiator:

- Beta+75-15-20-15
- Beta+75-15+00-15

Impact on system design

The hot case non-operational is used to define the maximum non-operational environmental temperature of the Tracker radiators. This temperature defines the maximum temperature (and therefore pressure) of inclined liquid between frozen parts in the condenser section.

Start-up hot case

For cold start-up the following worst case cold is defined:

- Tracker heat load 0 Watt
- Star Tracker heat load 0 Watt
- TTCS Pump cooling 0 Watt
- Health (survival) heaters (radiator, liquid lines) on
- Hot orbit (hot USS)

The following orbits are defined as hottest orbits for the TTCB (component box) interfaces.

The hottest cases for the TTCB-Primary are

- Beta+75-15-20-15
- Beta+75-15+00-15

The hottest cases for the TTCB-Secondary are:

- Beta-75-15+25+15
- Beta-75-15+15+15

Impact on system design

The start-up hot case is used to check whether the TTCS is capable to start-up in hot orbits. In case the environment (USS structure) is in such a case too hot (>30 °C) and the TTCB pump inlet reaches the same temperature. The TTCS is not capable to start-up in liquid mode.
In parallel tests are performed to start-up the TTCS system in supercritical-vapour conditions. These tests were successful but start-up takes longer time and that is an unfavourable.

3.3.7 Requirements during transfer (non-operational)

During transfer orbit the thermal environmental conditions are different from the conditions on the ISS truss.

Worst case cold

Important is to check the worst case cold non-operating case for the TTCS-boxes.

- Tracker heat load 0 Watt
- Star Tracker heat load 0 Watt
- TTCS Pump cooling 0 Watt
- Health (survival) heaters (radiator, liquid lines) off
- Cold case transfer orbit

To define this worst case cold USS temperatures during transfer should be identified. (This will be done in co-operation with CGS). It is assumed that the health heaters are switched off during transfer (i.e. power down).

Impact on system design

The cold case in power down during transfer might be the coldest case in power down mode. These environmental conditions might therefore be used to verify condenser design. It should be verified that the tubing from the box to the condenser manifolds stays above –50 °C.

Worst case hot

Another important issue is the environmental load, which can increase the radiator temperature from a freezing situation to melting. This would happen in the worst case hot non-operating.

- Tracker heat load 0 Watt
- Star Tracker heat load 0 Watt
- TTCS Pump cooling 0 Watt
- Health (survival) heaters (radiator, liquid lines) off
- Hot case transfer orbit

Impact on system design

In case the environmental solar input during transfer is large it could induce hot spots on the radiator. An extreme case during transfer might be the design driver for the freezing test and test procedure.

3.3.8 Vibration and Shock requirements

The TTCS-P, TTCS-S-box and the TTCE box should be able to withstand the vibration and shock requirements for Space Shuttle launch and transportation.

The vibration and shock requirements testing for the TTCE electronics will be according to **Environmental requirements for AMS Tracker Electronics,** Revision 1.0. by CAEN Aerospace S.r.L.. TTCE vibration testing is performed at in CSIST in Taiwan.

The TTCB-component boxes are subjected to Minimum Workmanship Level Vibration testing. The profiles can be found in RD-15. The testing is performed at the SERMS laboratory in Italy.

3.3.9 EMI requirements

The EMI requirements are found in:

DEPARTMENT OF DEFENSE INTERFACE STANDARD, MIL-STD-461E ”REQUIREMENTS FOR THE CONTROL OF ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS OF SUBSYSTEMS AND EQUIPMENT”, 20 AUGUST 1999

3.3.10 EMC requirements

EMC requirements are found in: International Space station Program office, “Space Station Electromagnetic Emission and Susceptibility Requirements”, Revision F 17 May 2001. More information on EMC techniques can be found in: Space Station Program Office, “Space Station Electromagnetic Techniques”, Revision D, 22 December 1998.

The verification of EMI/EMC for TTCE is performed at CSIST in Taiwan. The TTCB verification is performed at the CEM laboratory in Terni Italy according to RD-16.

3.3.11 Cosmic Radiation

TTCE follows the general rules for radiation tolerant components. For more information on AMS02 TTCE radiation tolerant design, contact Vladimir Koutsenko or Mike Capell.

4 TTCS Concept selection

4.1 Introduction

In Figure 4-1 a schematic of the AMS and the AMS TTCS system is shown. The objective of the cooling system is to collect the dissipated heat at the tracker electronics and transport the heat to two dedicated radiators. One radiator is located at the top Wake side and the other one at the RAM side of the AMS instrument.

The heat producing elements, the tracker front-end hybrid electronics are situated at the periphery of the tracker silicon planes and are located inside the cryogenic magnet. A total of 144 Watt is produced at 192 locations and an additional 6-10 Watt cooling capacity is required for additional electronics. The temperature requirements for the silicon waver and the front-end electronics are:

Silicon wafer thermal requirements	**Hybrid circuit thermal requirements**
Operating temperature: -10˚C / +25˚C	Operating temperature: -10˚C / +25˚C
Survival temperature: -20˚C / +40˚C	Survival temperature: -20˚C / +40˚C
Temperature stability: 3˚C per orbit	Temperature stability: 3˚C per orbit
Maximum allowed gradient between any silicon: 10.0˚C	
Dissipated heat: 2.0 W EOL	Dissipated heat: 144 W total (±10%) 0.75 W per hybrid pair (S=0.47 W, K=0.28 W)

Other critical TTCS-requirements for ASM-02 are:

- Compatibility with the existing Tracker Hardware.
- Limited volume.
- Multiple and widely distributed heat inputs up to 160 W.
- Minimal temperature gradients of less then 1^{o}C
- Low mass budget < 72.9 kg, low average power budget < 80 watt.
- High reliability i.e. fully redundant system design.
- Two radiators thermally out of phase (see also Appendix II).

The detailed requirements are found in the former section (section 3). As mentioned in section 2 the TTCS design had to be adapted to a cryo-cooled magnet with little thermal mass. In the section the concept selection of the two-phase pumped cooling system is presented illustrating the design constraints leading to this selection.

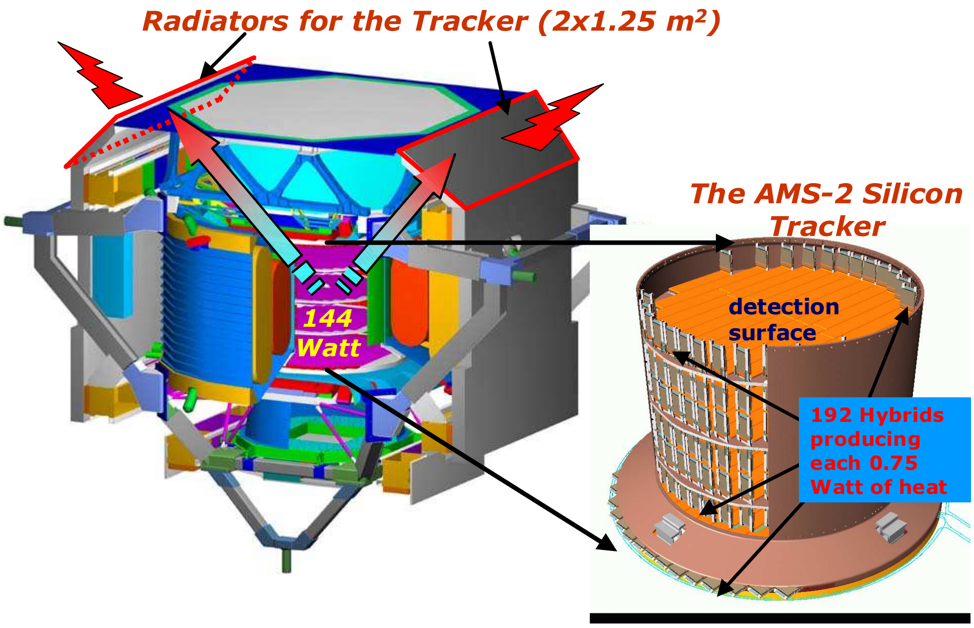


Figure 4-1: AMS Silicon Tracker Schematic

4.2 Concept selection

In the concept selection to come to the current design, three designs were considered:

1. Capillary pumped systems
2. Single phase pumped systems
3. Two-phase pumped systems

Capillary pumped systems consisting of loop heat pipes and heat pipes are widely used in satellite thermal control. Large advantage is therefore the flight heritage and experience with these systems. However, with the lay-out of the widely distributed heat input, no Loop Heat Pipe construction inside the Tracker is possible due to the limited size of LHP evaporators. Alternatively a two-stage approach could be followed. Collecting the heat inside the Tracker with heat pipes and transporting the heat to a number of loop heat pipes. However this leads to considerable hardware and mass inside the Tracker. With the required redundancy the volume available is not sufficient to accommodate series of parallel heat pipes.

A **single-phase mechanically pumped loop** requires little volume inside the tracker the heat can be collected by a tube routed along all heat sources. The collected heat is then transported to the radiators and rejected to deep space. To fulfil the temperature gradient requirements inside the tracker the mass flow will be relative high compared to the two-phase pumped system. Where the single-phase system uses the sensible heat, a two-phase system uses the latent heat and can therefore transport in the order of 100-1000 times more heat with the same mass flow. Drawback and concern of both the mechanically pumped single-phase and two-phase systems is the presence of a pump. For reliability reasons redundant pumps are foreseen in each separate redundant loop.

A **two-phase pumped loop** has large advantages to account for the AMS TTCS design challenges. It provides an almost isothermal environment for all the 192 distributed electronics elements as the heat is collected by evaporating fluid inside a tube. The temperature rise will be in the order of 1 K. The tube diameter size will be small (< 3 mm) compared to single phase systems and the required pumping power will be small (< 10 Watt).

A quantitative comparison between a single-phase and a two-phase pumped loop is given in Table 1 and based on:

- System Properties general
  Dissipated heat = 154 W
  Tubing: L= 73 m (length), t= 1 mm (thickness), stainless steel
  Mean velocity in tubing = 1 m/s
  System Pressure head ~ 1.6 bar
  Efficiency pump ~ 35%
  Carbon dioxide properties at 0 º C
- System Properties 1-phase
  Maximum temperature gradient in evaporator ΔT = 2 K
- System Properties 2-phase
  Maximum vapour quality in evaporator X = 0.35

	Single-phase	Two-phase
Mass Flow	31 g/s	2.25 g/s
Pump Power	15 Watt	1.1 Watt
Mean tubing diameter (based on a 1m/s mean flow velocity)	6.3 mm	1.8 mm
Fluid mass	2.1 kg	0.2 kg
Tubing mass	13 kg	5 kg
Total mass (excl.components)	15.1 kg	5.2 kg

Table 4-9: Comparison between a two-phase and single-phase CO2 pumped loop

The table shows the mass benefit of the two-phase system over the single-phase system. Drawback of the two-phase pumped system is the lack of sufficient flight heritage and the presence of a pump. However the system easily fulfils the envelope requirements and is more mass effective than the alternative solutions.

As a capillary pumped system does not fit in the available volume inside the tracker, the two-phase mechanically pumped loop is finally chosen as preferred concept. The main advantages over the single-phase system are the almost perfect isothermal operation, the low mass, the small volume, and the low pump power required.

4.2.1 Working fluid selection

With a two-phase pumped loop as baseline the working fluids are limited to fluids with a boiling temperature in the operating range of the pay-load.

Other working fluid requirements are:

- Low liquid/vapour density ratio
- Boiling temperature range: -10 ºC to +20 ºC
- Temperature survival range –100 ºC to + 65 ºC
- Safety: Non-toxic
- Radiation resistant fluids
- Working pressure

High vapour flow velocities induce considerable pressure drops in the evaporator part of the loop. Apart from the additional pumping power needed to circulate the flow, a pressure drop also induces a temperature gradient in the saturation temperature along the evaporator. Working fluids with high liquid/vapour density ratios are therefore unfavourable as they introduce either large diameter piping in the evaporator or cause large temperature drops. Another important issue is safety. Non-toxic working fluids are preferred in view of the amount of fluid required (approx. 2 litre) and the Space Shuttle safety requirements.

Candidate fluids for the two-phase pumped system were among others; ammonia, carbon dioxide, freon-like fluids. Ammonia is the most common working fluid used in satellite cooling systems and has large flight heritage. However the large liquid/vapour density ratio in the order of 102-103 is unfavourable. Also the system safety is a point of concern for system integration and tests. Freon-like fluids also have the disadvantage of having a high liquid/vapour density ratios, in the order of 102. Other drawbacks are the limited radiation resistance of some fluids and the unknown behaviour of mixtures in micro-g environment. Carbon-dioxide finally, has a low liquid/vapour density ratio in the order of 1 to 10 ideal for low pumping power (< 10 W), allows small tube diameters (d ≈ 3 mm), and induces only small temperature drops in the evaporator (< 1 K). Additional advantages are the proven radiation resistance (nuclear power plant cooling) and the low toxicity of carbon dioxide. Although it has a high working pressure and therefore a high design pressure (160 bar) carbon dioxide is selected as the preferred working fluid as it combines the advantages of low toxicity, low temperature drop in the evaporator and low pumping power.

5 TTCS System Description

The system lay-out for the primary loop is shown in Figure 5-1. The loop lay-out for the secondary loop is shown in Figure 5-2. The main functionality of the TTCS loop is to transport heat dissipated by the tracker electronics to radiators that radiate the heat to deep space.

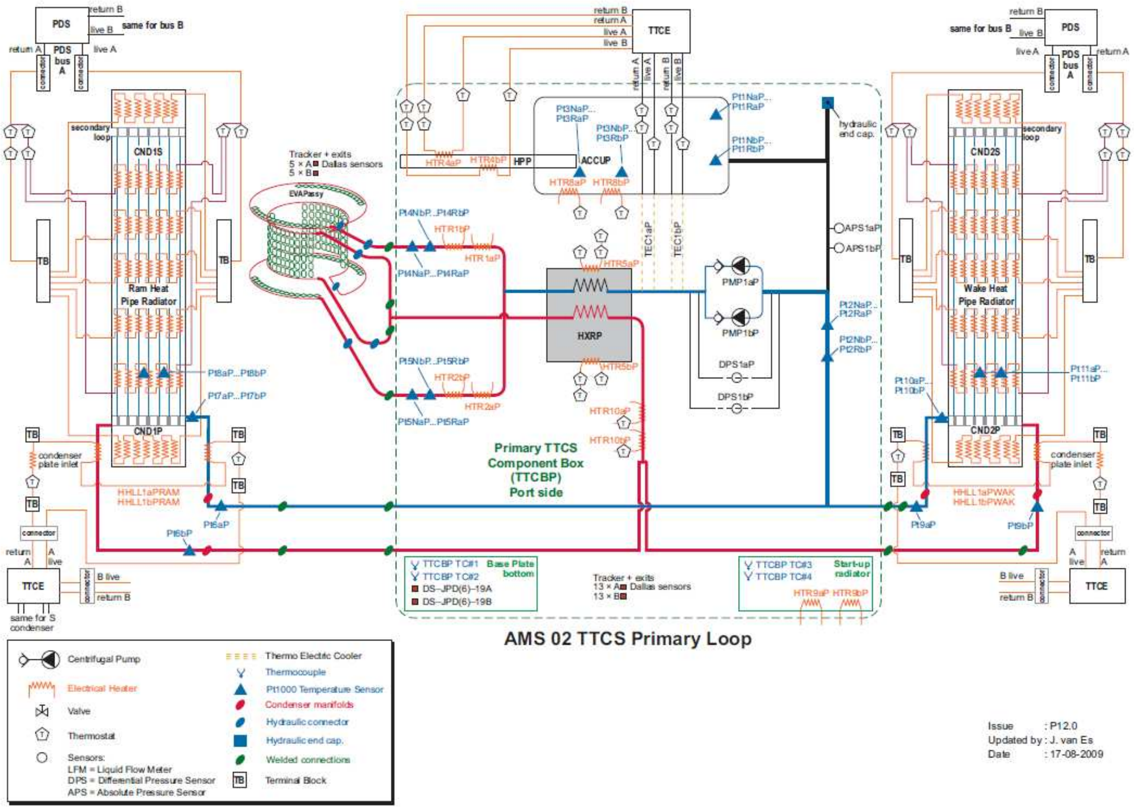


Figure 5-1: Schematic of the Tracker Thermal Control System Primary Loop

For reliability reasons, two redundant loops will be implemented. In Figure 2-2, the layout of the primary TTCS-loop is given. The secondary loop is a hydrodynamic complete independent copy of the first one except that the tube length to the inlet of the evaporator is slightly larger. By following the loop routing in 2-1 and 2-2 the loop operation is explained. At the pre-heaters the working fluid temperature is lifted to the saturation temperature. The working fluid enters the evaporator with a quality slightly above zero, ensuring a uniform temperature along the complete evaporator. Due to the widely distributed front-end electronics the evaporator consists of two parallel branches collecting the heat at the bottom and top side of the Tracker planes. At an overall mass flow of 2 g/s the mean quality at the outlet of the evaporators is approximately 30%.

The two-phase flow of both branches is mixed and led through the heat exchanger where heat is exchanged with the incoming subcooled liquid. Behind the heat exchanger the two-phase line (red) is split. One branch leads to the condensers at the RAM heat pipe radiator and the other is lead to the condensers at the WAKE heat pipe radiator. At the radiators the heat is rejected to space.

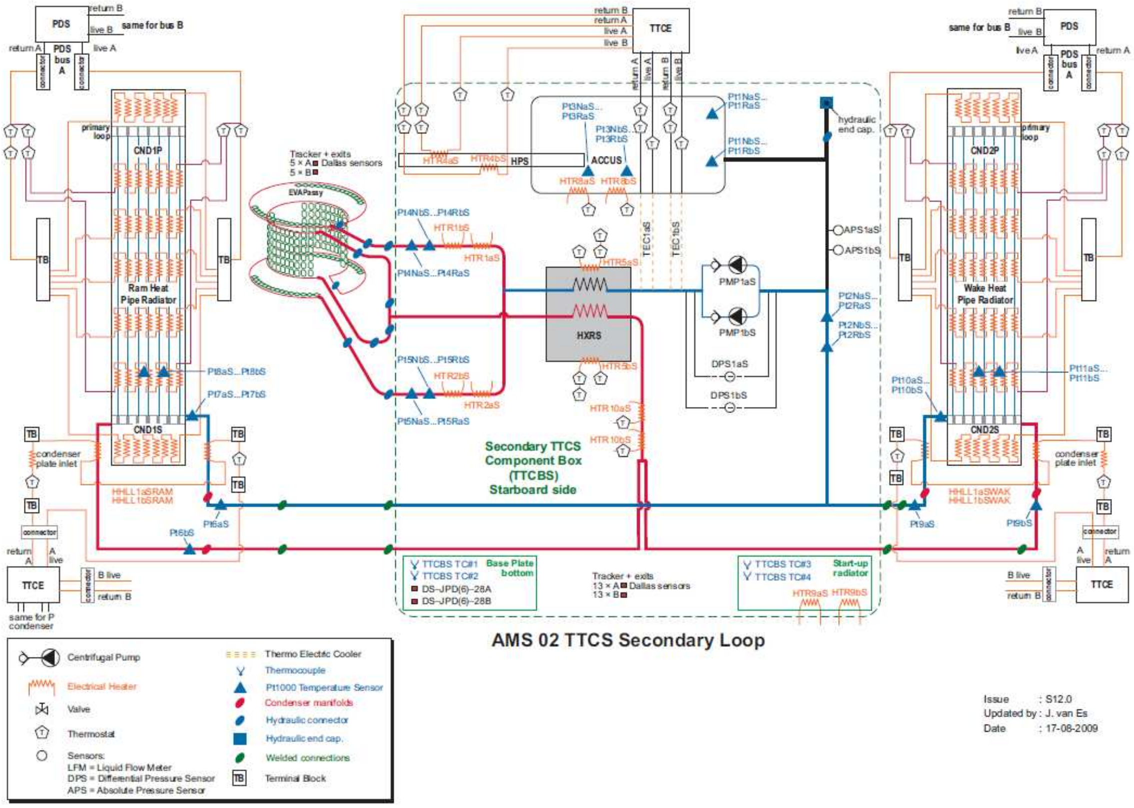


Figure 5-2: Schematic of the Secondary Loop

After the mixing point of the two radiator branches, the sub-cooled fluid passes the accumulator. By controlling the accumulator temperature the evaporator set-point temperature is controlled by Peltier elements (cooling) and heaters. The set point can be varied to avoid extreme sub-cooling or operation with liquid temperature just below saturation at the inlet of the pump. A distinct amount of sub-cooling is required to avoid cavitation at the pump. Behind the pump the sub-cooled fluid is warmed up in the heat exchanger before it enters again the pre-heater section.

5.1 TTCS Breadboard and Engineering model results

To demonstrate the feasibility and show the ability of the TTCS loop to adapt to changes in environmental conditions a TTCS breadboard was build. The results illustrate the TTCS-operation.

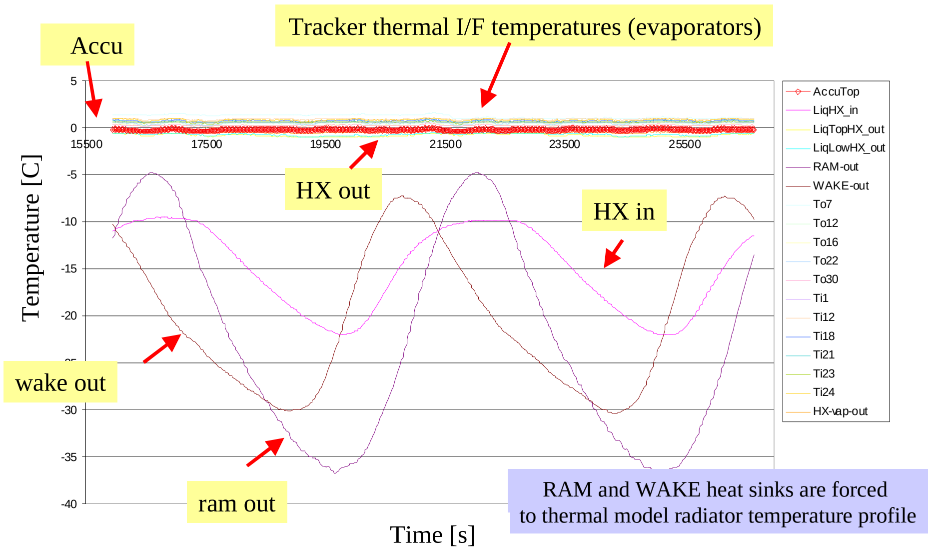


Figure 5-3: NLR TTCS Breadboard result with a forced temperature profile on the radiators

In Figure 5-3 a breadboard test is shown. A realistic temperature profile is forced on the radiators by cold plates. It is clearly shown that the evaporator temperatures are isothermal and well within the required temperature band of 3 K per orbit.

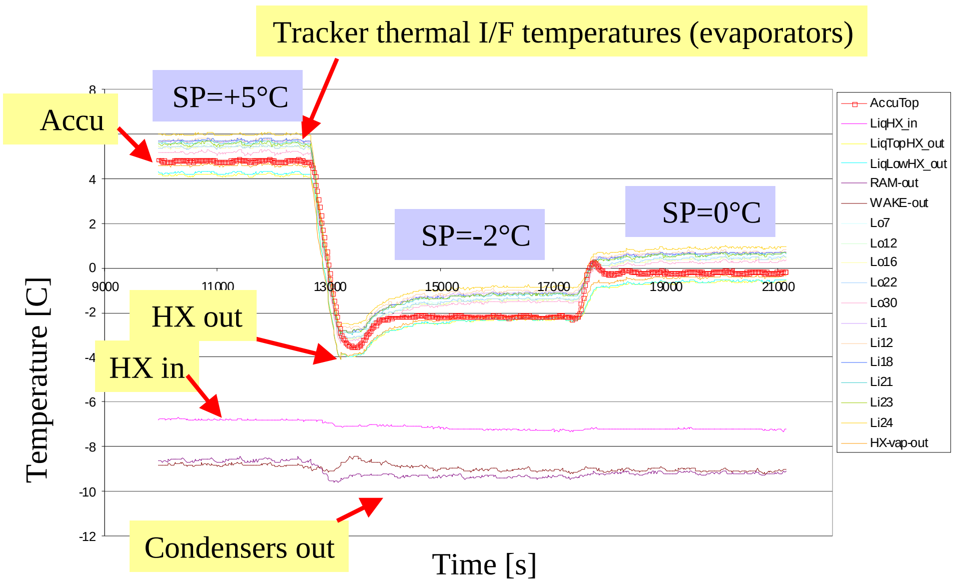


Figure 5-4: Set point changes

In Figure 5-4 the result of a breadboard test with set point changes is shown. The results show that the evaporator follows the set-point changes and the evaporator stays isothermal. The same results are repeated during the Engineering Model and Qualification Model phases of the TTCS development. A complete Engineering Model loop with the exact tube lengths and lay-out is build at the Sun Yat Sen University.

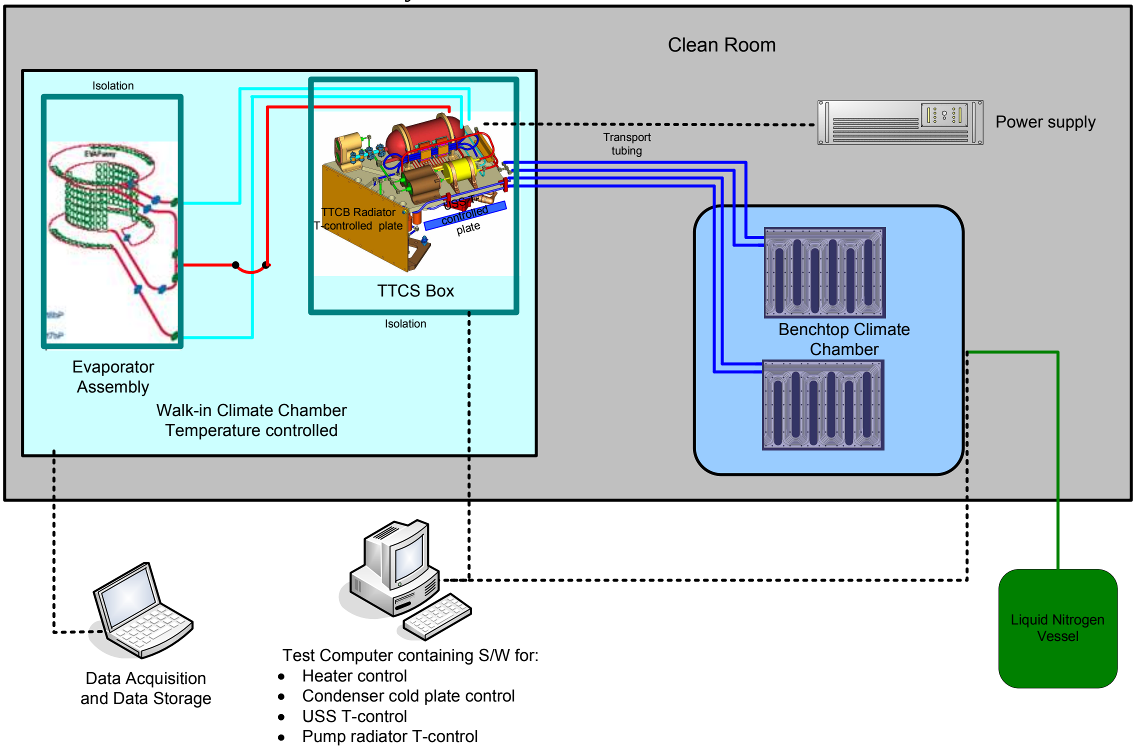


Figure 5-5: TTCS Engineering Model Test Set-up schematic

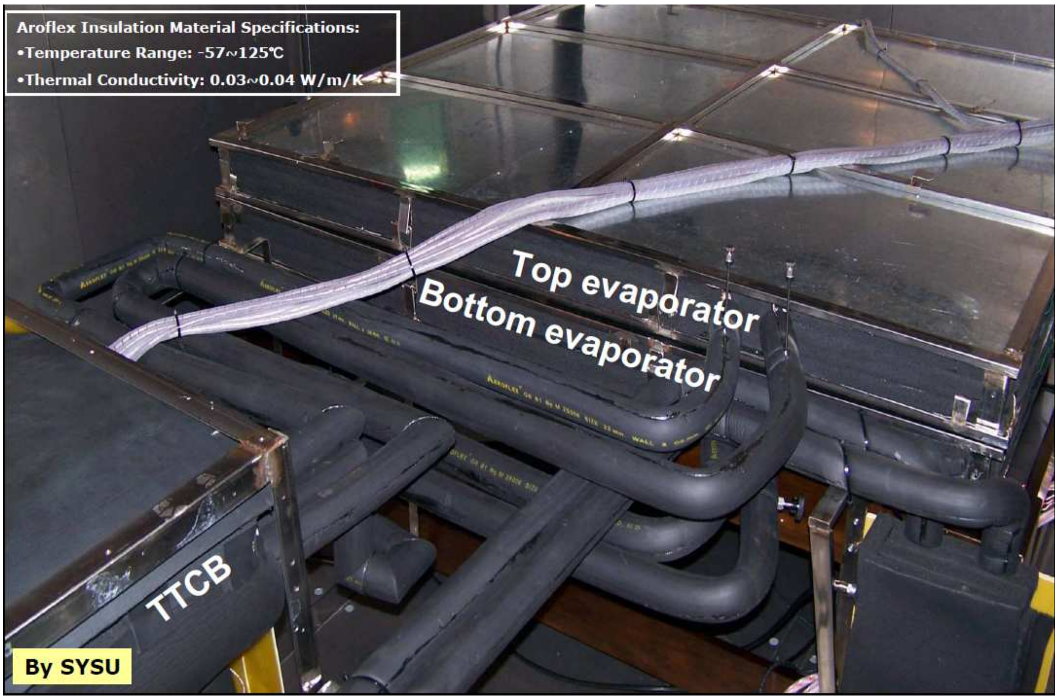


Figure 5-6: TTCS Engineering Model Evaporator

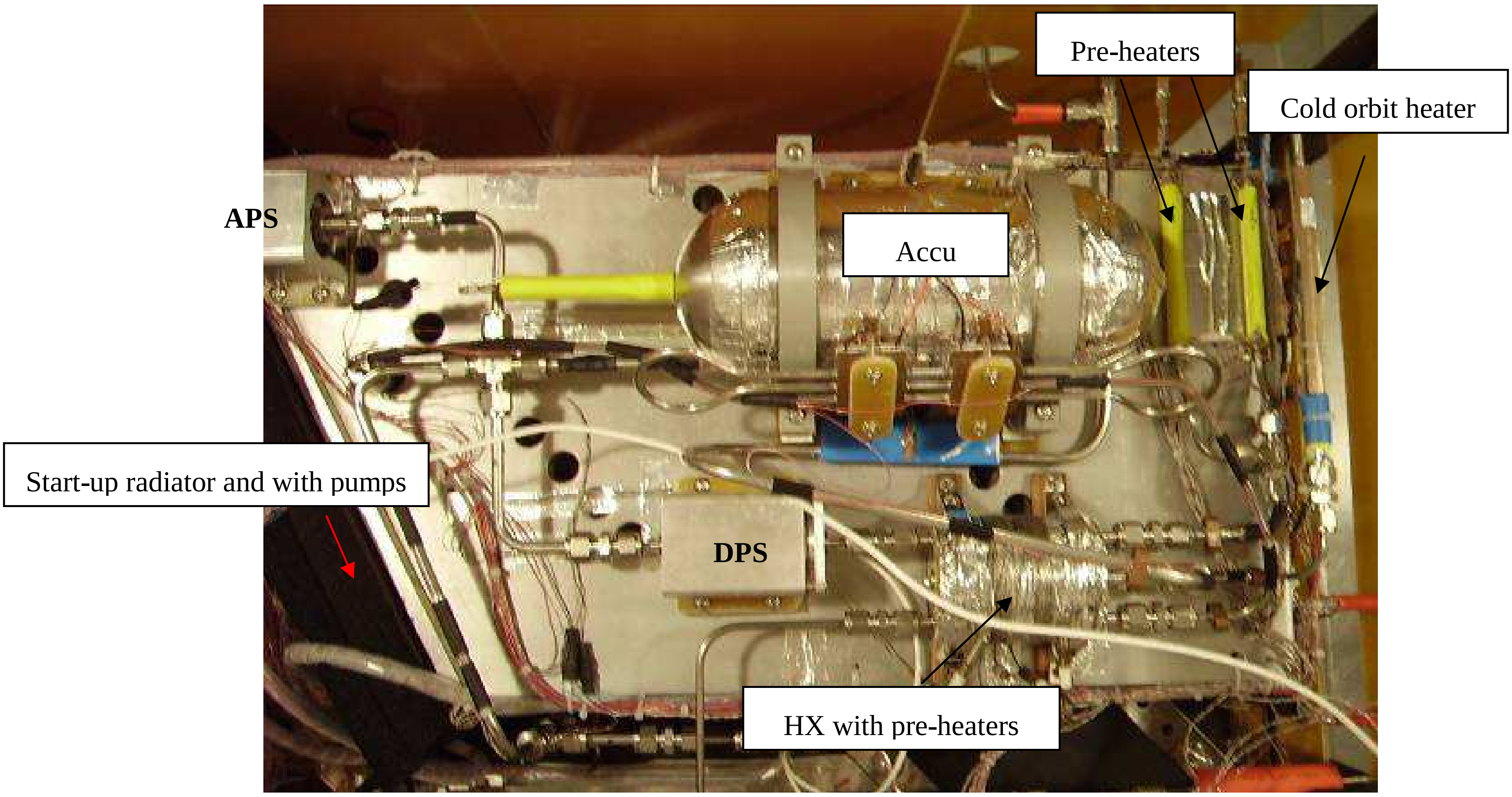


Figure 5-7: TTCB Engineering Model lay-out

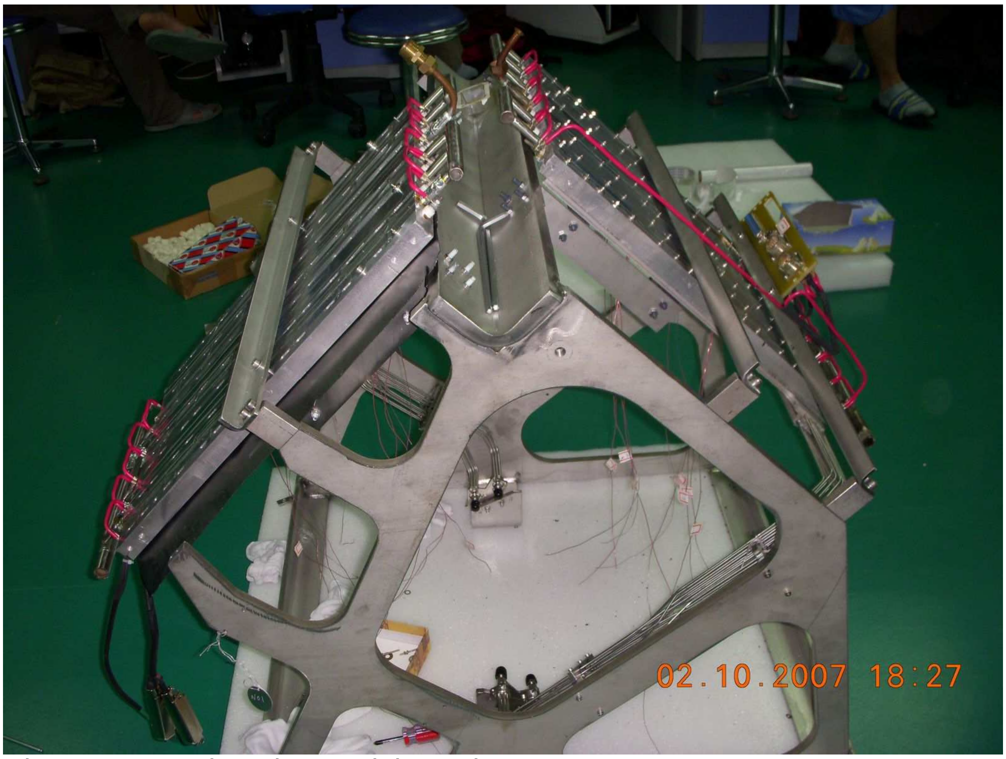


Figure 5-8: Engineering Model Condensers

Also with the TTCS Engineering model realistic orbital temperature profiles can be simulated by nitrogen cold plates as interface with the condensers. An extensive test program has been performed to verify Tracker thermal stability and proper control in μ-g and 3D lay-out in nominal and extreme environmental conditions (RD-17, RD-18 & RD-19). In the figure below the thermal stability is shown with large variations in Tracker evaporator load.

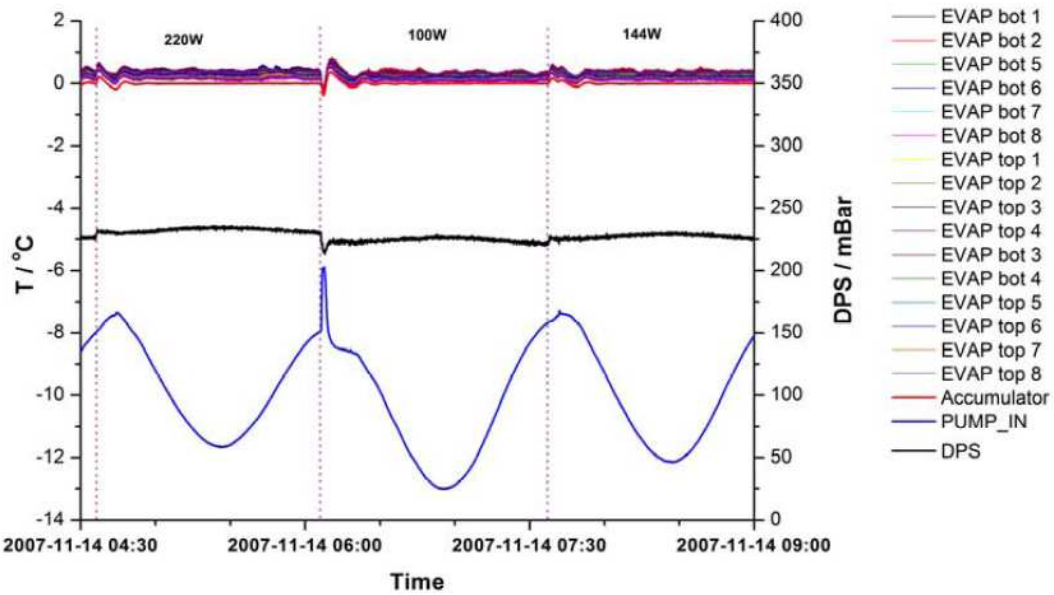


Figure 5-9: Tracker thermal stability under varying heat loads

5.2 TTCS Hardware locations

TTCS hardware is widely distributed over AMS02 as it transports the heat from the Tracker at the centre of AMS to the Tracker radiators located on the RAM and Wake top sides.

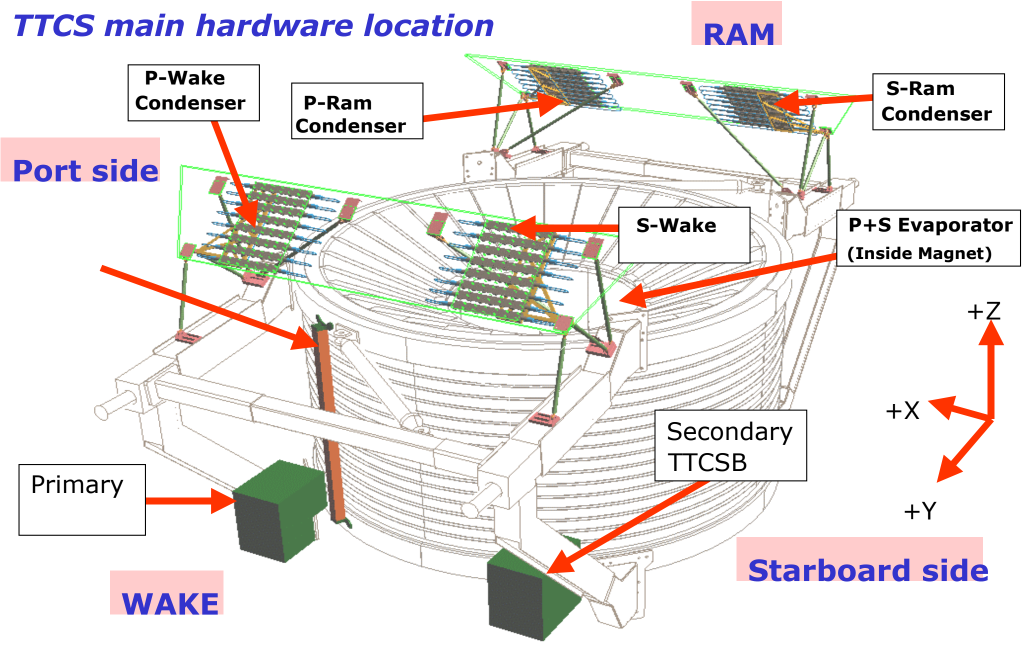
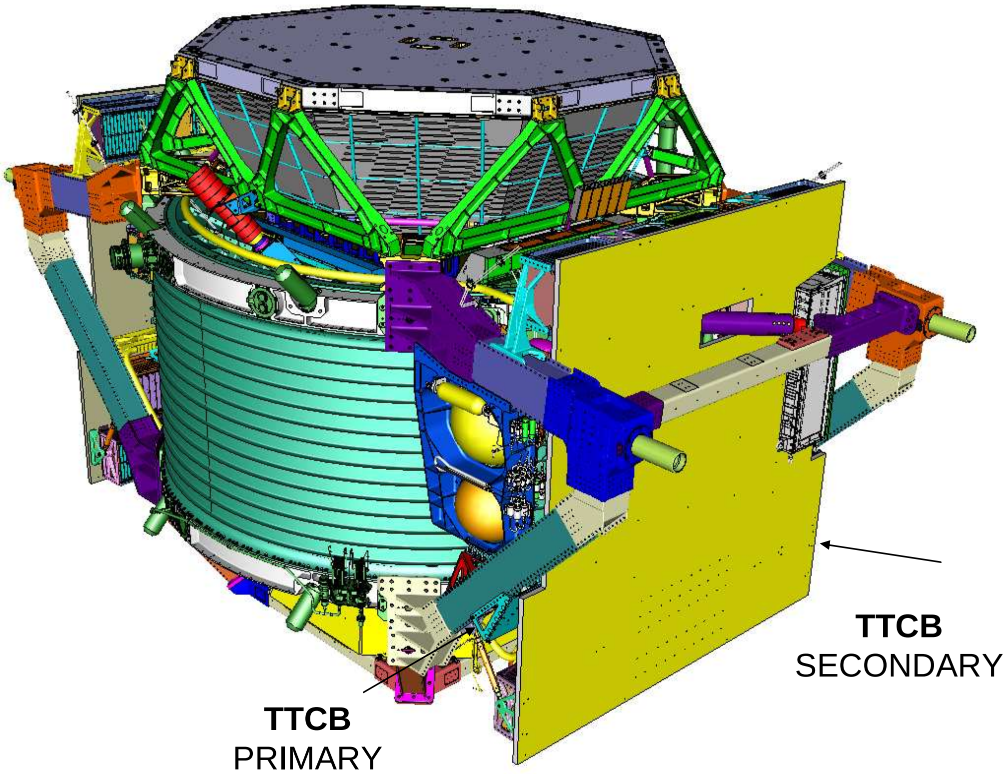


Figure 5-10: Location of TTCS Hardware

Two complete redundant systems are integrated. The Primary loop is located on the Port side and the Secondary loop is located on the Starboard side. Each system consists of the five main components:

- Evaporators (2 per loop, one at the bottom and on at the top)
- Tracker Thermal Control Box (TTCB)
- Condensers (2 per loop)
- Transport tubes to connect the components
- Tracker Thermal Control Electronics (TTCE)

The heart of the TTCS loops are the Tracker Thermal Control boxes. In these TTCB's all components to operate the TTCS loops are combined. The TTCB are connected the AMS Unique Support Structure (USS) on the Wake side. Inside the magnet the TTCS bottom and top evaporators located. These thin-walled (0.2 mm) and 3 mm diameter tubes run at the bottom and the top of the Tracker to pick up the heat and keep the Tracker stable (< 3K/orbit) in temperature.



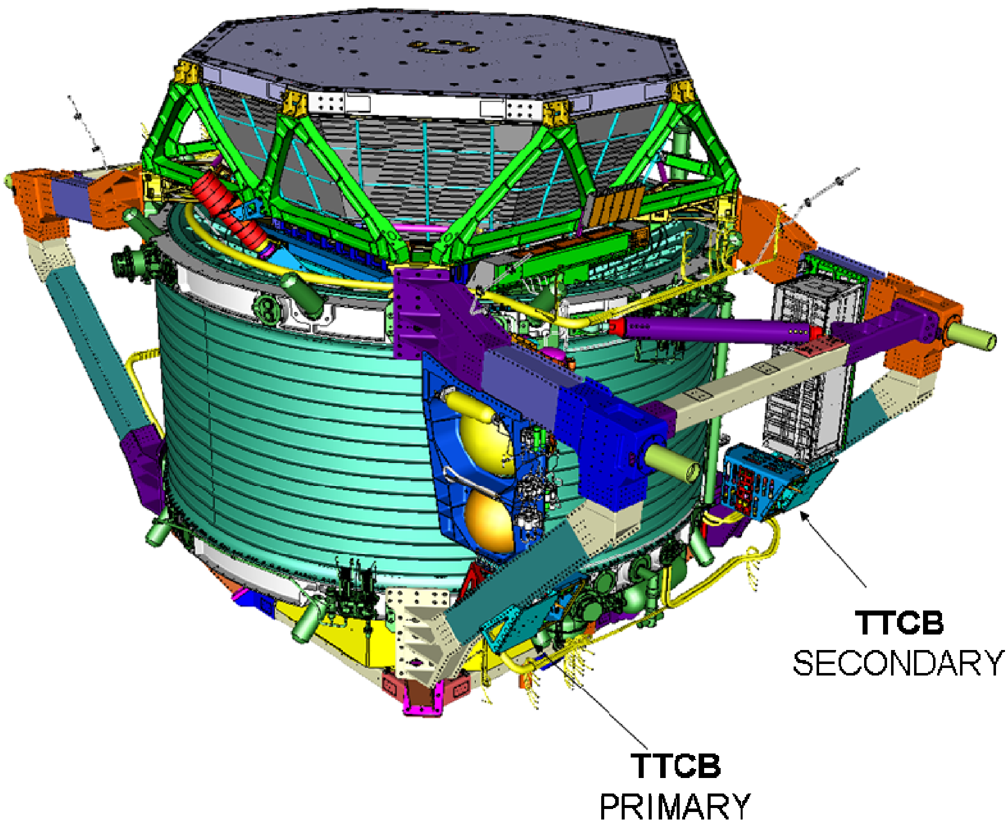


Figure 5-11: Location of the Thermal Tracker Control Boxes (Picture by C. Gargiulo)

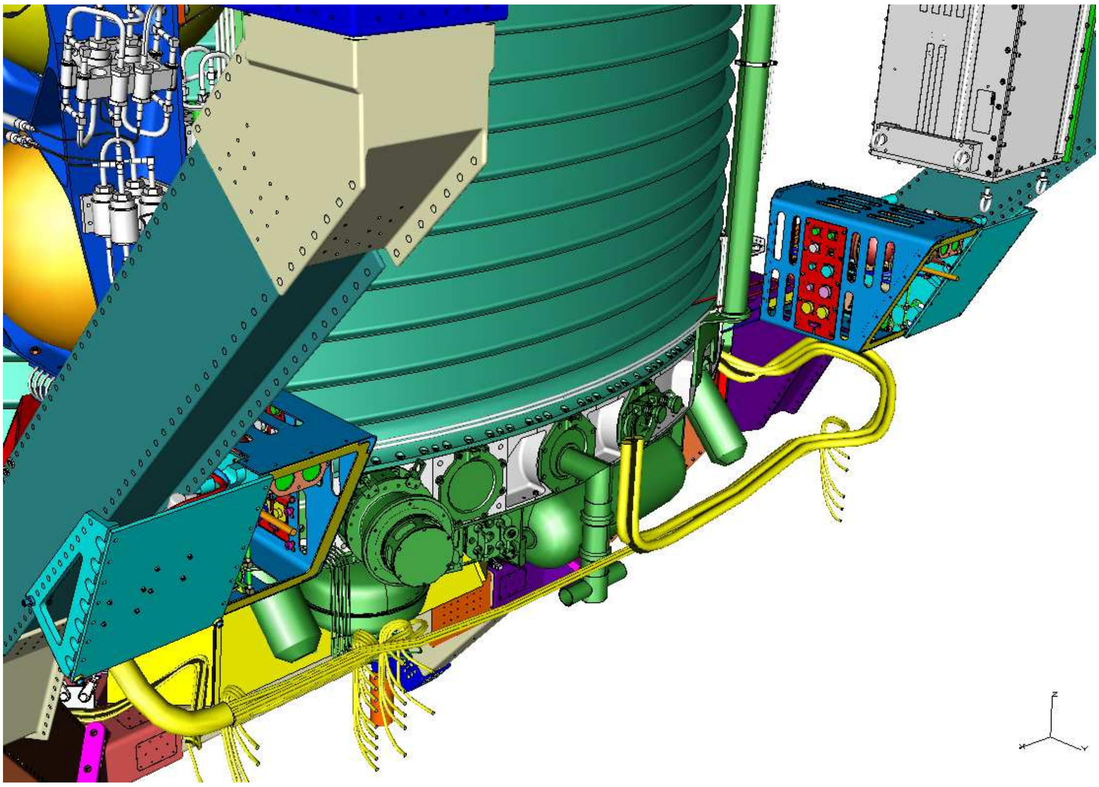


Figure 5-12: Detailed views of the TTCB locations (Pictures by C. Gargiulo)

The heat is rejected at the Tracker RAM and Wake radiators by the TTCS condensers. Each loop has one condenser on RAM-side and one on Wake side. The heat is further spread over the complete Tracker radiators by ammonia heat pipes.

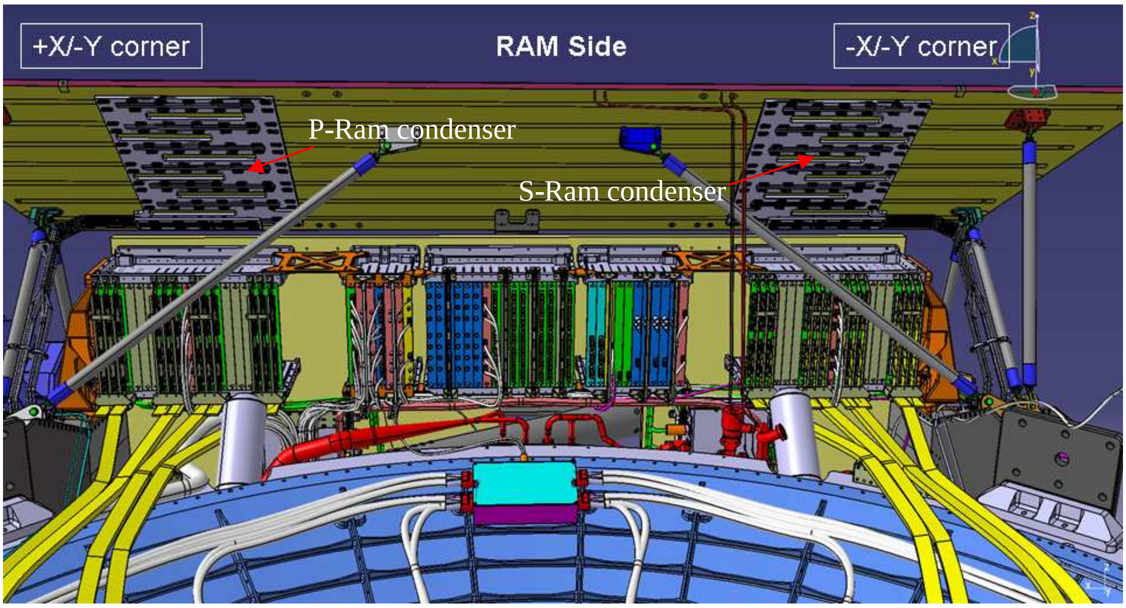


Figure 5-13: Location of TTCS condensers RAM (Pictures by F. Cadoux)

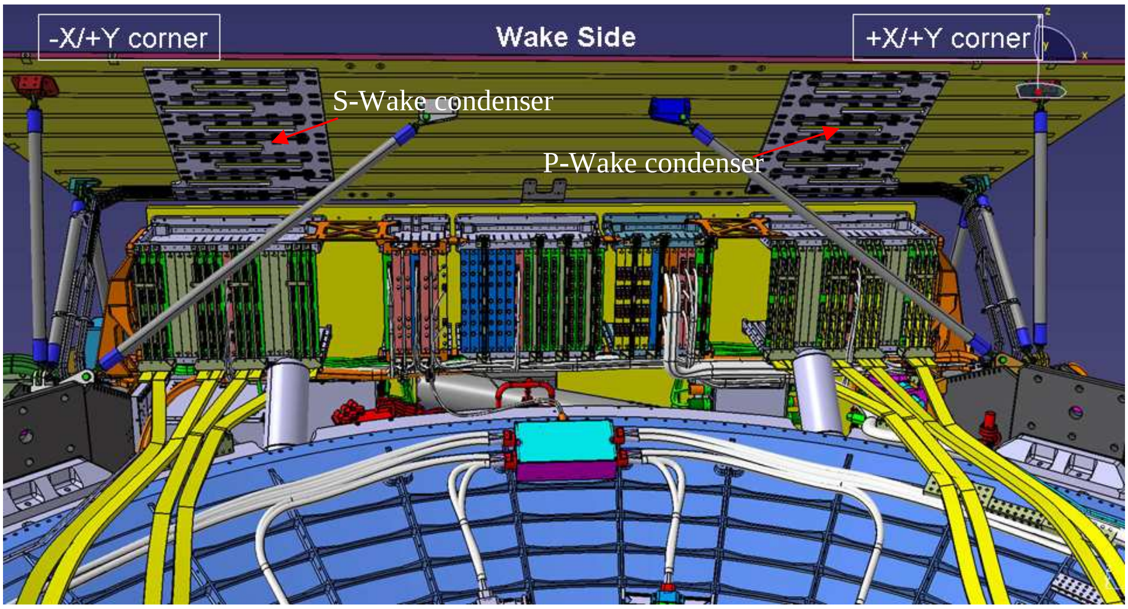


Figure 5-14: Location of TTCS condensers RAM (Pictures by F. Cadoux)

The RAM and Wake condenser, bottom and top evaporators and the TTCB of each loop are connected by transport tubes running along the conical flange and the Wake side Vertical Support Beams (VSB).

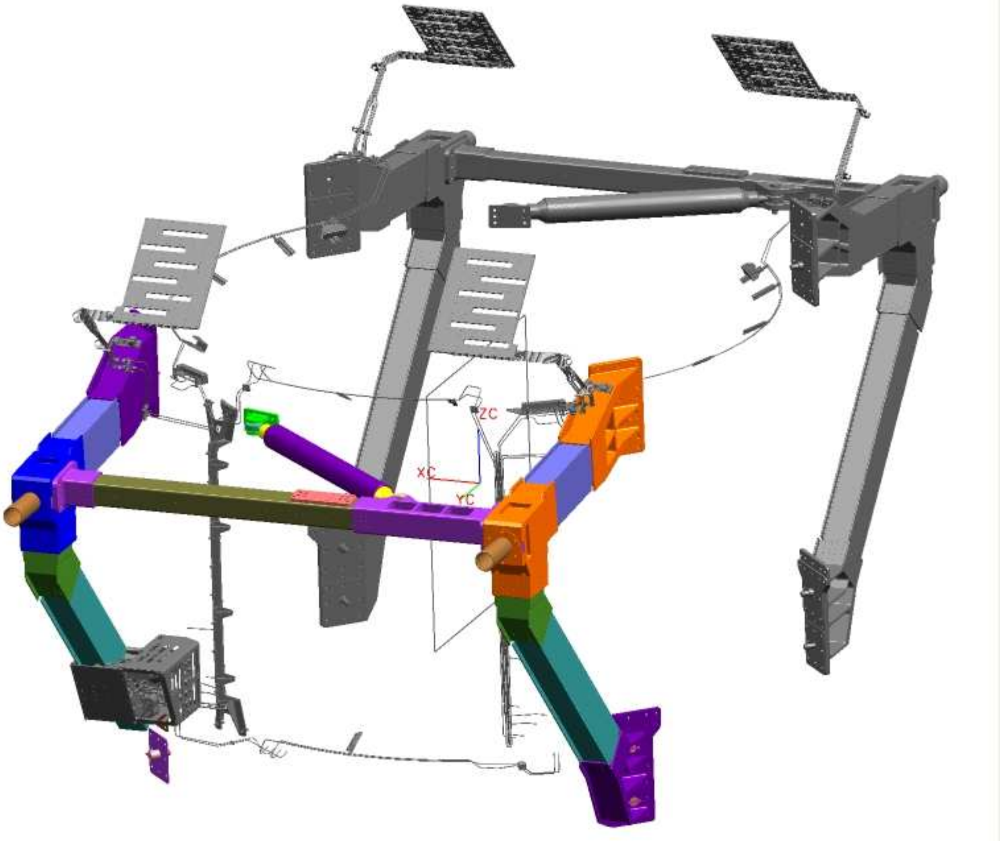


Figure 5-15: TTCS transport tube routing

The evaporator loops inside are connected to the transport tubes by hydraulic connectors to avoid welding needs to be done with a direct coupling via the tubes to the delicate Tracker electronics. The Secondary loop has additional hydraulic connectors at the box evaporator connections. These connectors are used to attach a mini-TTCS with cooling capacity during AMS02 beam testing. This mini-TTCS is needed to provide enough cooling capacity.

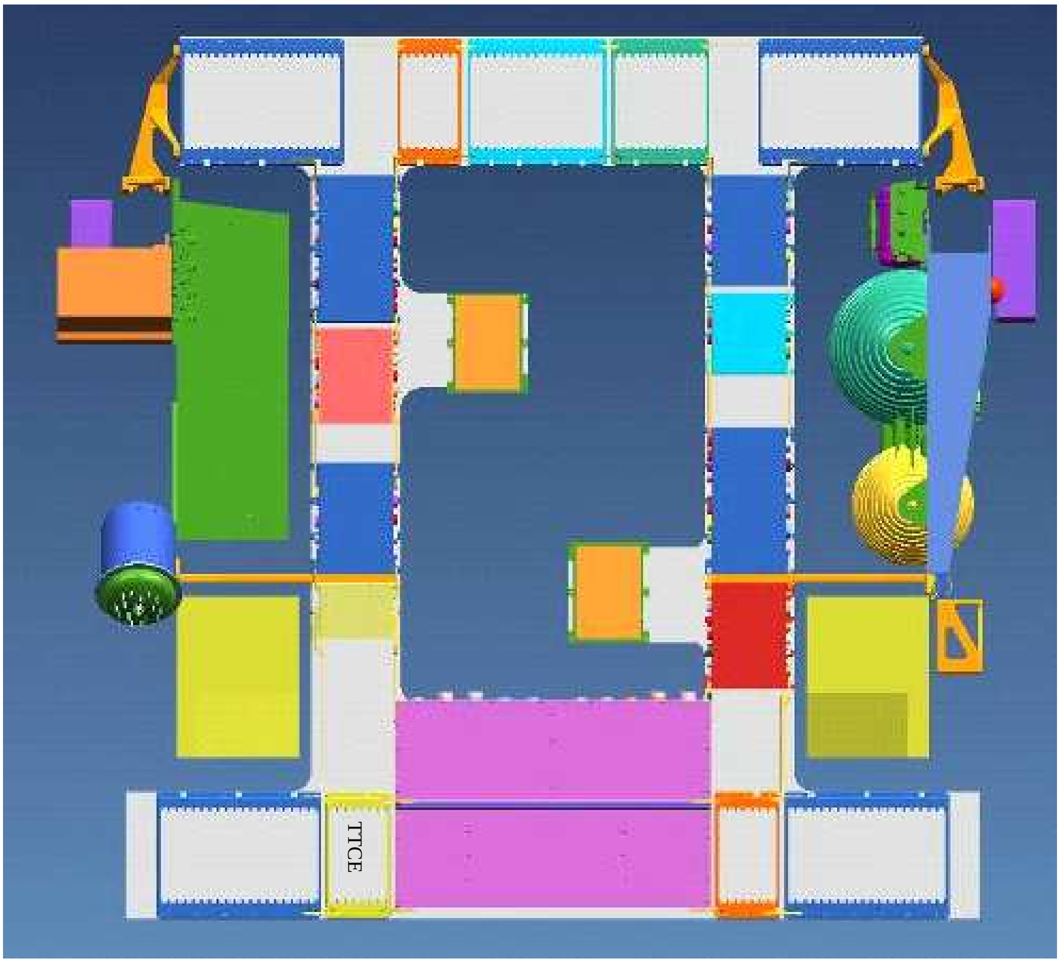


Figure 5-16: Location of the TTCE Electronics box on the Wake radiator

Both loops are operated by the Tracker Thermal Control Electronics (TTCE) located on bottom the main Wake radiator (see also section 7).

5.3 Components and functionality

In Table 4-10 all TTCS components are listed and their functionality explained.

Component	Function
Pump	Transport the fluid through the loop
Accumulator	Regulate the evaporator temperature in the tracker Account for the expansion of the working fluid
Accumulator Peltier elements	Regulate evaporation set-point in all operation modes (cooling)
Accumulator heaters	Regulate evaporation set-point in all operation modes (heating) Emergency accumulator heat-up in case liquid line temperature approaches saturation temperature (to avoid cavitation in pump)
Heat Exchanger	Exchange heat between hot evaporator outlet and cold evaporator inlet. Reduction of pre-heater power.
Evaporator	Collect heat at the tracker electronics. The evaporation process provides the temperature stability required.
Condensers	Remove the heat from the working fluid to the radiators. The condensing process makes the heat transfer effective.
Absolute Pressure Sensors	Monitor the absolute pressure inside the loop
Differential Pressure Sensor	Monitor pump pressure head
Pre-heaters	Heat evaporator liquid inlet to saturation point
Start-up heaters	Additional heater for cold start-up (off during nominal operation)
Cold Orbit heater	Additional heater to keep the condenser temperature above CO2 freezing temperature (-50 °C) during cold orbits
Liquid line health heaters	Heaters to defrost the condenser inlet and outlet lines after an AMS02 power down
Dallas Temperature Sensors	Monitoring TTCS temperatures (by the TTCE) Monitoring TTCS as part of the AMS overall GTSN Dallas sensor network
Pt1000 Temperature Sensors	Control accumulator temperature Control pre-heater on/off Monitor cold temperatures on radiator and liquid lines
Thermostats	Keep heated components below the maximum level required for safety
TTCB foil heaters (non-flight)	Keep TTCB above -40 °C during AMS02 TV testing

Table 4-10: Functional design of the loop

5.4 Thermal Tracker Control Box lay-out

Apart from the evaporators and the condensers all TTCS components are located in the TTCB's.

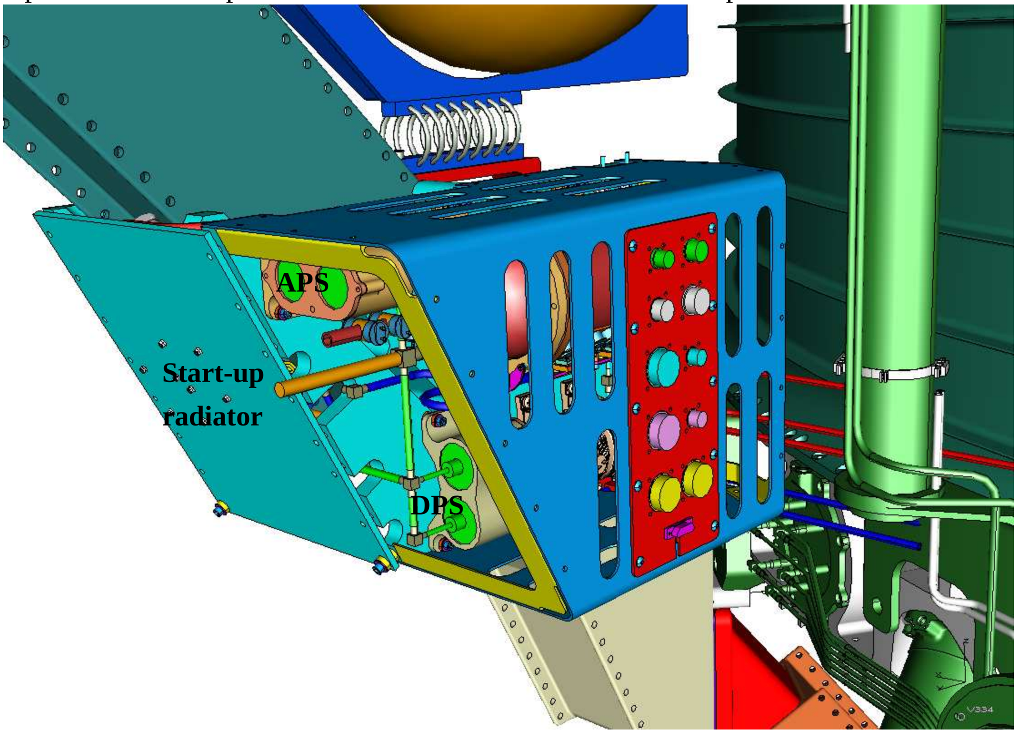


Figure 5-17: Primary TTCS box on port side of AMS (Picture by C. Gargiulo)

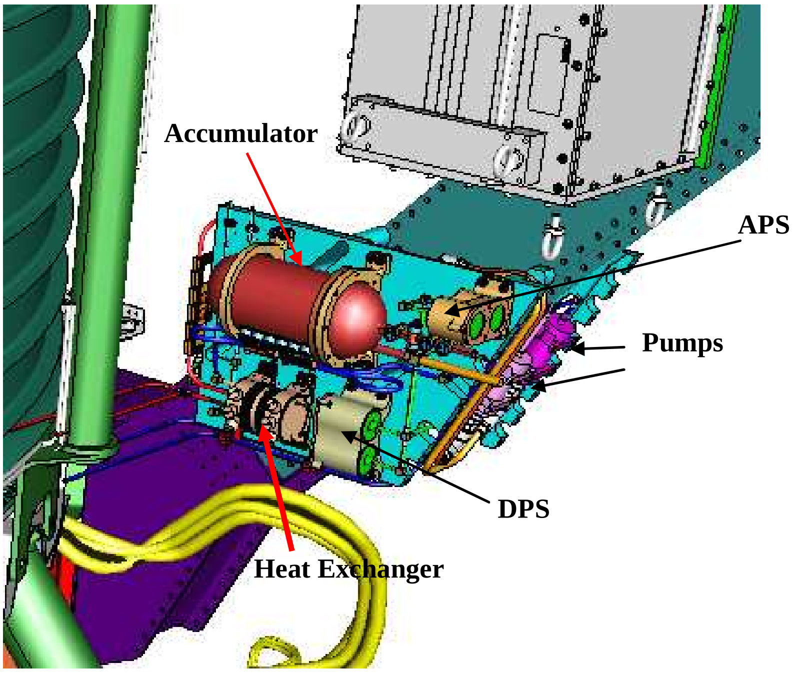


Figure 5-18: Secondary TTCS box on starboard side of AMS (Picture by C. Gargiulo)

The box contains the following components (Primary box numbering):

- 2 Pumps located on the start-up radiator (PMP1aP, PMP1bP)
- 1 Pump electronics controller box
- 1 Accumulator (ACCUP)
    - Accumulator control heaters Flight (HTR4aP, HTR4bP)
    - Accumulator Peltier elements Flight (TEC1aP, TEC1bP
    - Accumulator control heaters Ground (non-flight) (HTR8aP, HTR8bP)
- 1 Heat exchanger (HX) with 2 integrated Start-Up Heaters (SUP) (HTR5aP, HTR5bP)
- 4 Pre-heaters (HTR1aP, HTR1bP, HTR2aP, HTR2bP)
- 2 Cold Orbit Heaters (COH) (HTR10aP, HTR10bP)
- 2 Absolute Pressure Sensors (APS1aP, APS1bP)
- 2 Differential Pressure Sensors (DPS1aP, DPS1bP)
- Pt1000 temperature sensors
    - Control Pt1000's
        - (Pt1NaP, Pt1LaP, Pt1RaP,........ Pt5NaP, Pt5LaP, Pt5RaP)
        - (Pt1NbP, Pt1LbP, Pt1RbP,........ Pt5NbP, Pt5LbP, Pt5RbP)
    - Monitor Pt1000's
    - Pt6aP, Pt6bP..... Pt11aP, Pt11bP
- Dallas sensors (total 26 per box)
- LSS TTCB heaters (HTR9aP, HTR9bP)
- Thermostats (total 20 per box)

Most TTCB components are located on the TTCB base plate under an aluminium cover.

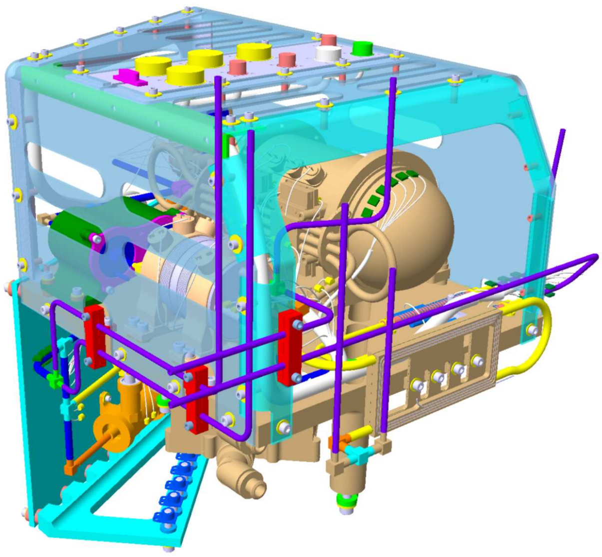


Figure 5-19: TTCB-Primary final design

The box cover and base plate sides are wrapped in Multi Layer Insulation (MLI) to insulate the components from the environment. Titanium (thermally insulating) washers are used to reduce also the heat leak to and from the USS. The TTCS pumps are the single components not located on the base plate. The pumps are located on a special start-up radiator. This start-up radiator radiates to the back side of the main wake radiator providing a lower temperature then the TTCB I/F with the USS. This is needed to increase the orbital time window for normal (liquid) TTCS start-up. The pump temperature should therefore be lower then the accumulator temperature and the CO_2 critical temperature (+33 °C).

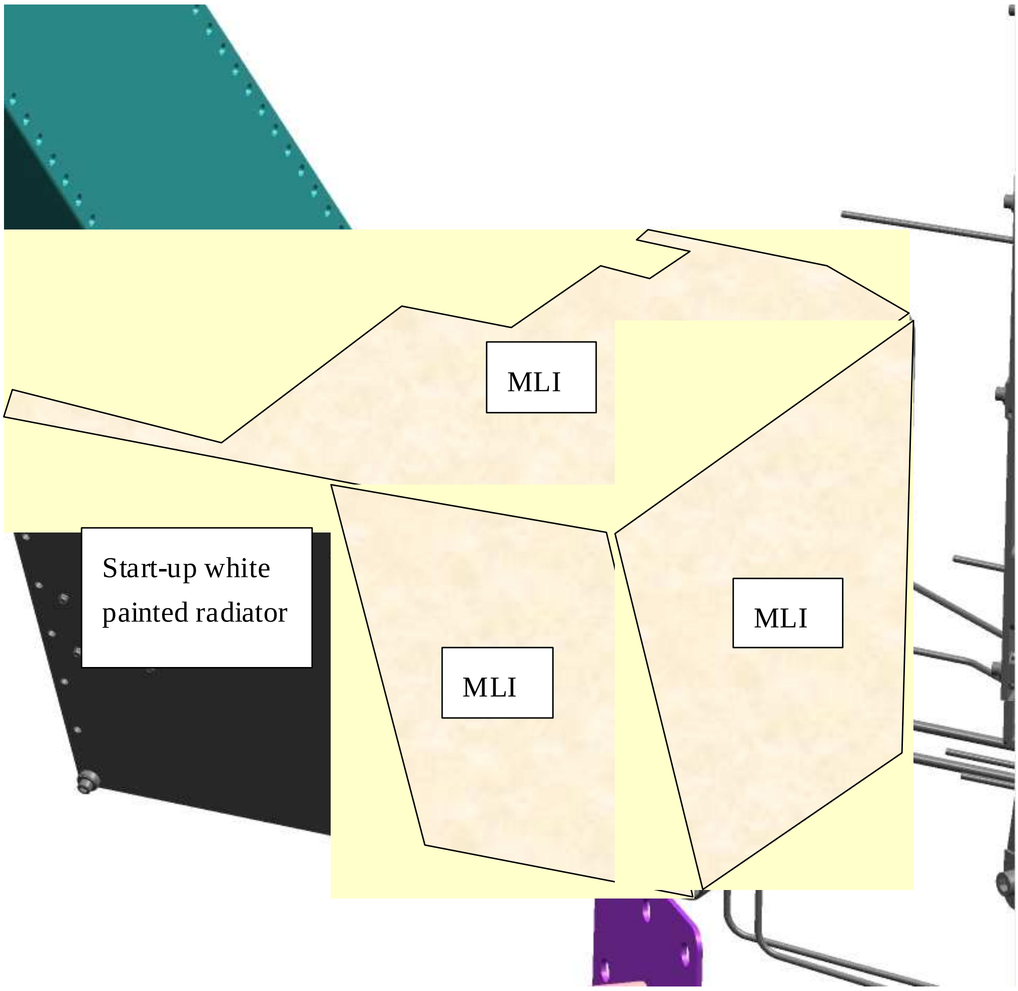


Figure 5-20: Schematic of MLI wrapped around the TTCB (Sketch by C. Vettore)

The detailed box assembly is shown in Figure 5-21 and Figure 5-22 for respectively the Primary box and Secondary box. More detailed information on the box can be found in the TTCB drawing packages (RD-21 & RD-22).

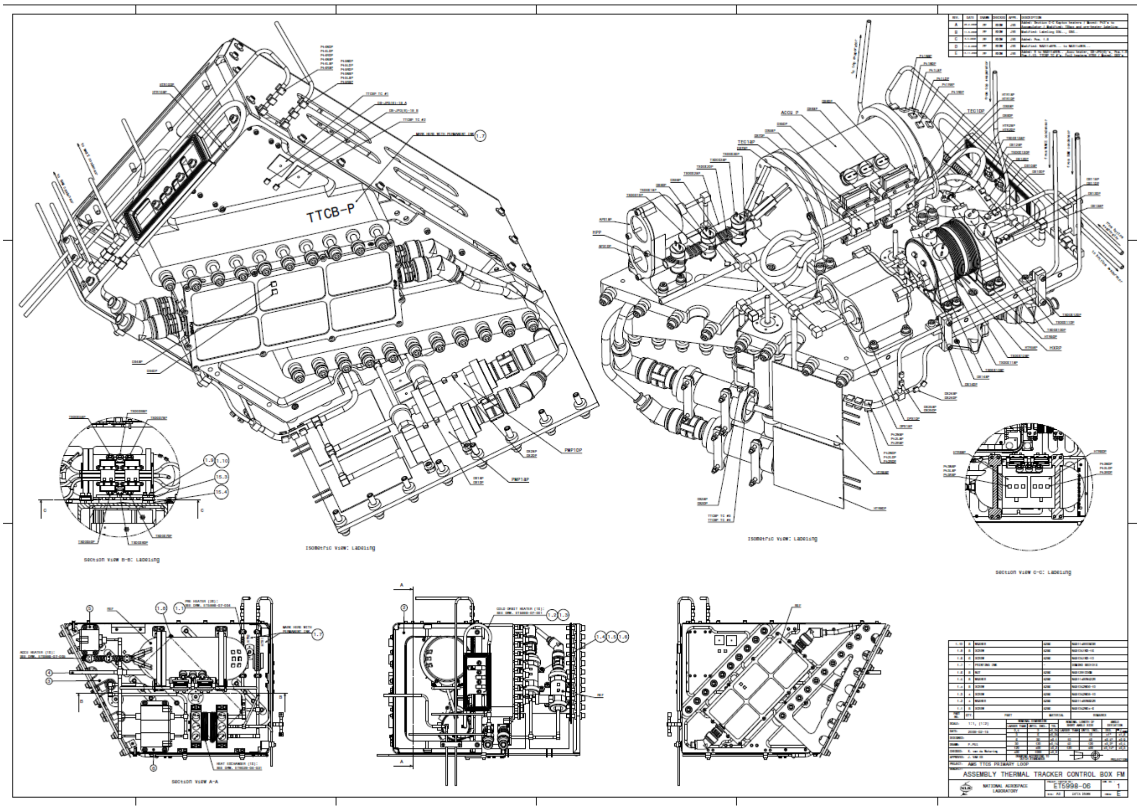


Figure 5-21: TTCB-P box assembly (NLR detailed design)

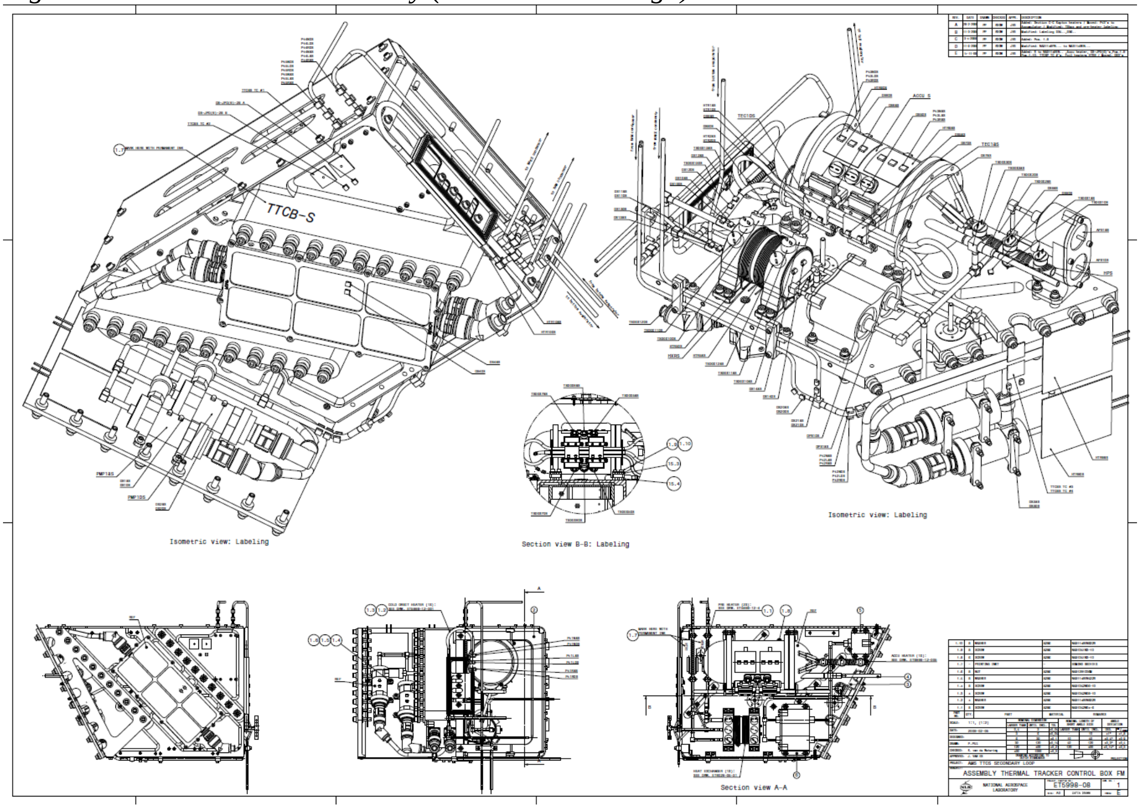


Figure 5-22: TTCB-S box assembly (NLR detailed design)

In Figure 5-23 and 5-24 pictures of the integrated boxes are shown.

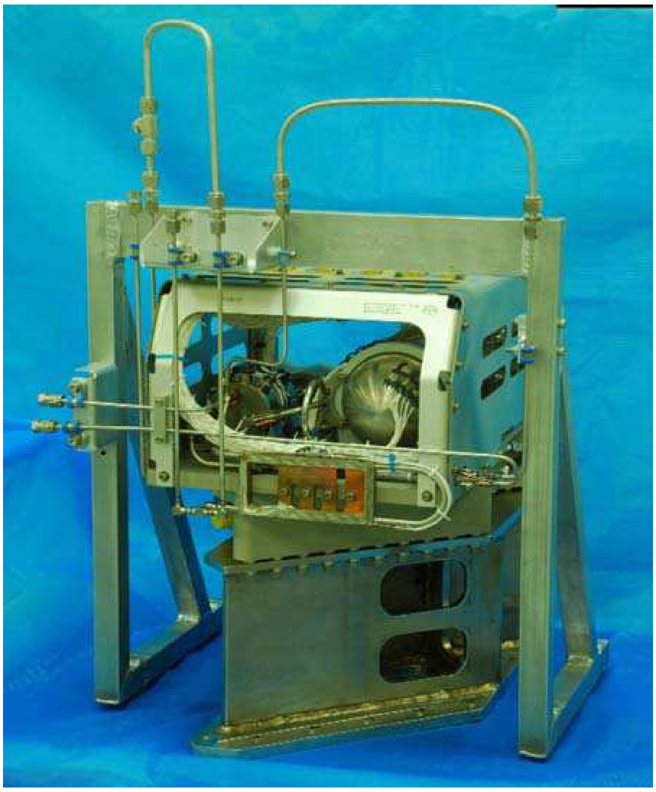


Figure 5-23: TTCB-P box assembly on USS simulator and in vibration frame

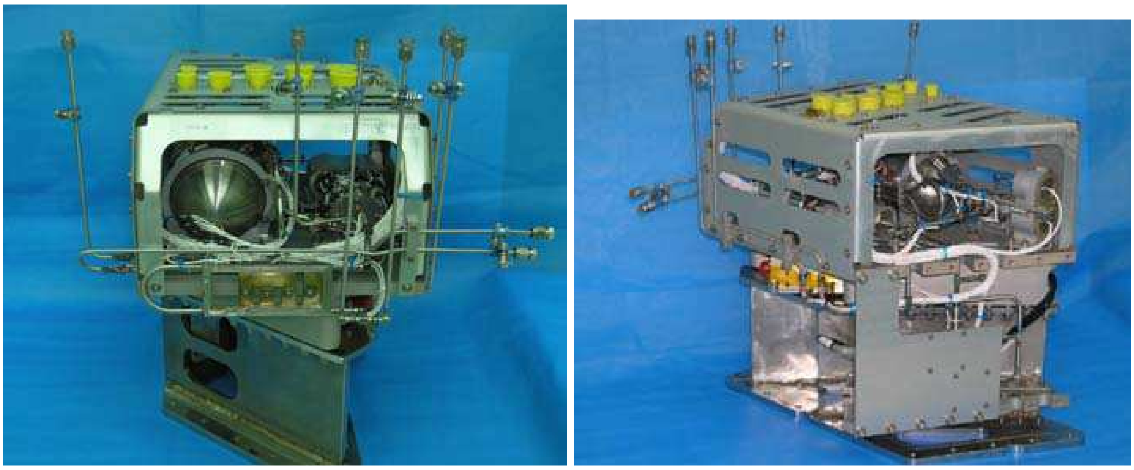


Figure 5-24: TTCB-S box assembly front and back side

In the following sections loop components are presented and the designs elucidated.

5.5 Pump assembly

The most critical component in the loop is the pump. The pump provides the fluid flow in the TTCS. Each TTCS-loop is equipped with two pumps for redundancy reasons. The location of the pump electronics controller box and the pumps is shown below. The pump electronics controller box is located near the pumps to minimise the lengths of the pump cabling ("dirty" high frequency signals).

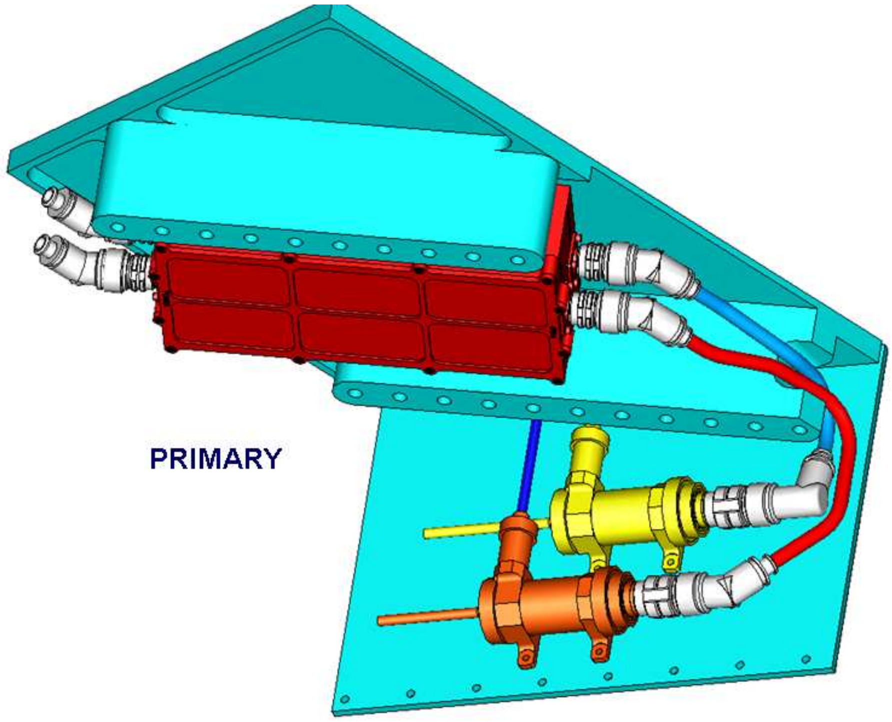


Figure 5-25: Pump Electronics Controller Box and Pumps in TTCB-P

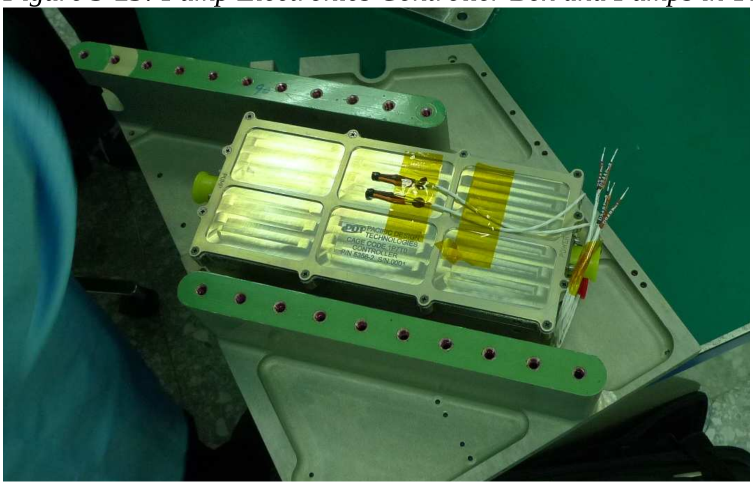


Figure 5-26: Pump Electronics Controller Box in TTCB-P

5.5.1 Pump design

Pacific Design Technologies (Santa Barbara, USA) developed the TTCS pump. The designed pump is a single-stage centrifugal pump and based on the PDT Mars Pathfinder pump. The pump housing is an all-welded design to cope with the high design pressures and strict leak tightness requirements. The pump performance curves are rather flat. This is due to the fact that the pump has to operate in low flow rate area (1-4 g/s) with rather high pressure heads 100-850 mbar. In terrestrial application a gear pump would be selected. In view of the life time TTCS selected a centrifugal pump.

Figure 5-27: PDT Pump Engineering Model (QM and FM are similar)

5.5.2 System curve

The system curve as defined in the NLR breadboard loop are shown in Figure 5-28. The calculated performance curve is shown in Figure 5-29. The nominal flow rate is 2 g/s.

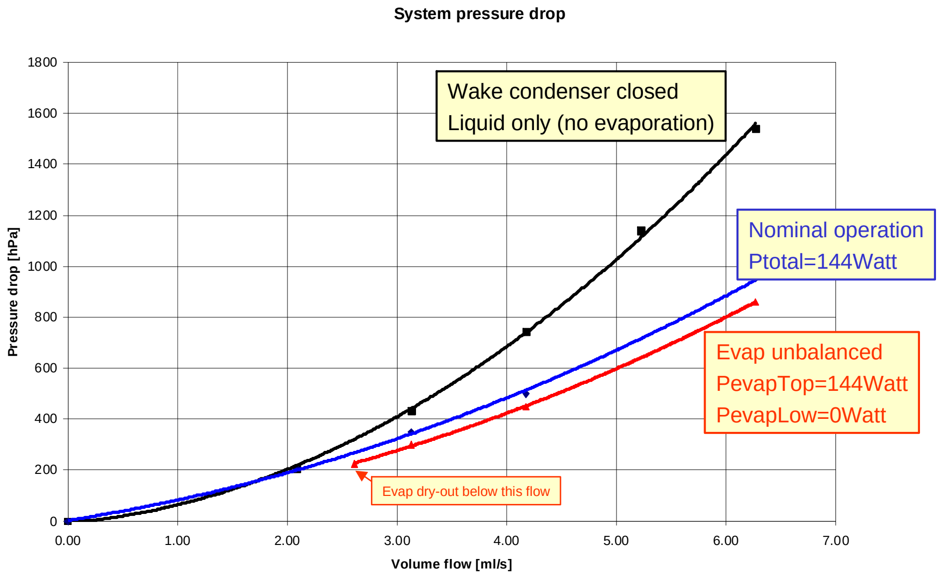


Figure 5-28: TTCS system pressure drop (experimental data with TTCS Breadboard)

The blue line shows the curve for nominal operation with 144 Watt dissipated power on the loop. The black line shows the pressure drop with one closed condenser. The red line is the result of an experiment with totally unbalanced evaporator branches. This means all dissipated heat (144 Watt) is put in one branch. Downto a flow of 2.7 ml/s no dry-out occurred in the parallel branch. Based on this data the pump curve requirements were defined.

- minimum flow rate 1 ml/s and 150 mbar
- maximal flow 4 ml/s at 850 mbar

5.5.3 Pump Performance curve

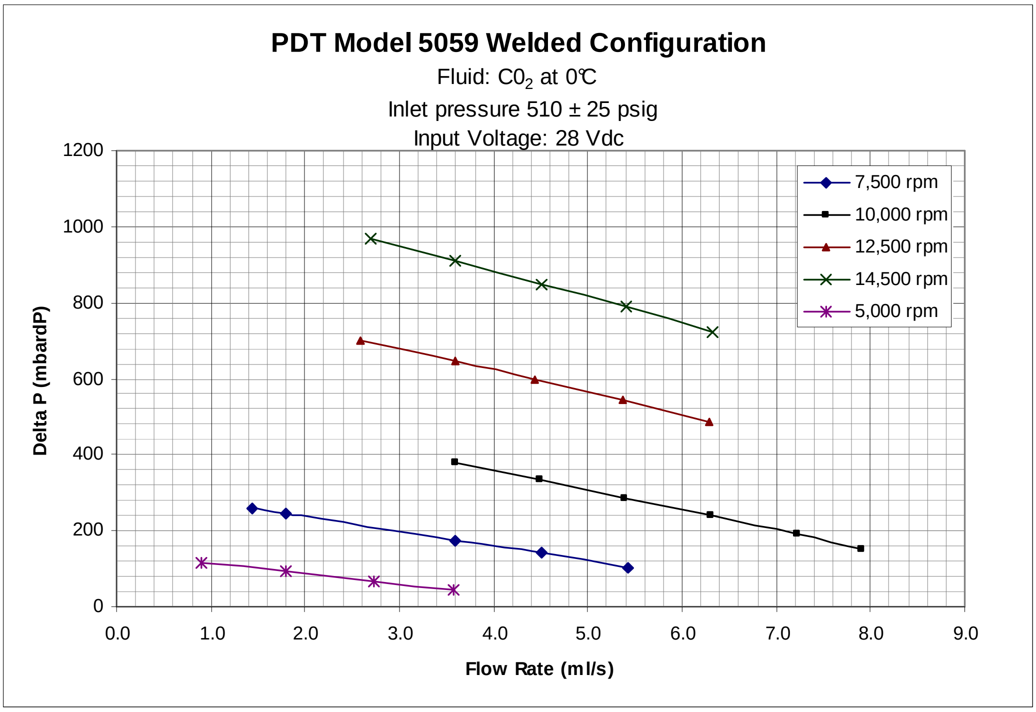


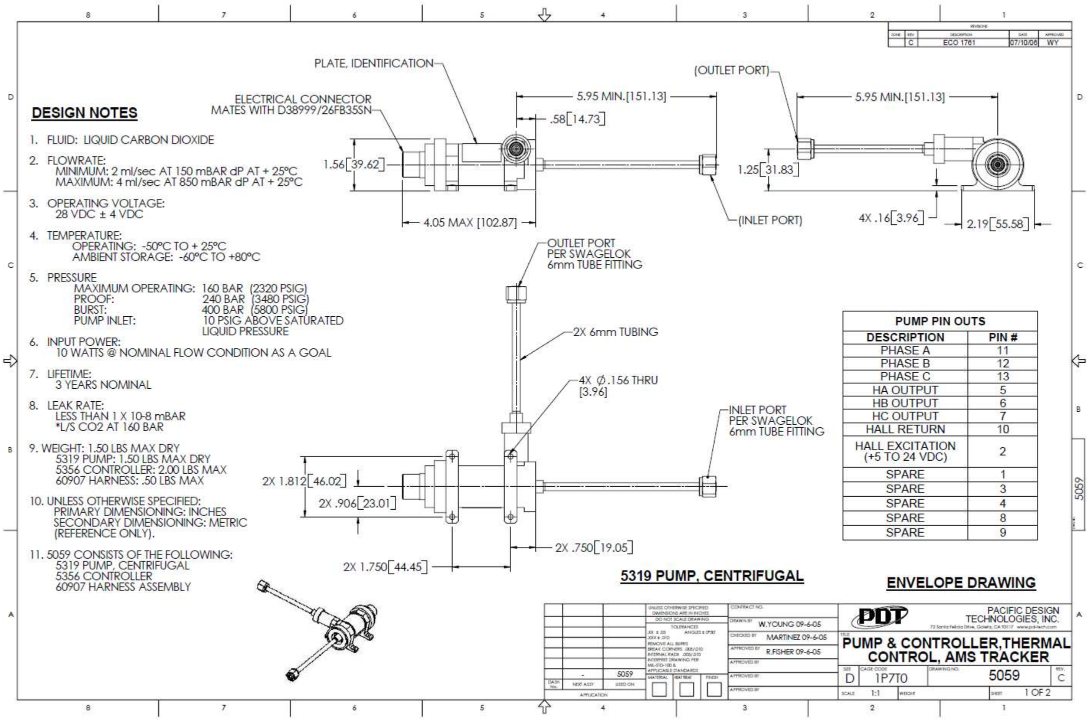
Figure 5-29: Pump performance curves (QM Pump)

The performance curve as tested by PDT shows the pump can deliver enough pressure head.

5.5.4 Pump Specifications

The pump specifications are shown in below design drawing. Additional to this the pump should also:

- Be compliant with the AMS02 environmental requirements
- Capable of operation in a magnetic field (140-1000 Gauss) (Hall-effect sensors)
- Be able to start-up in supercritical-vapour conditions



The EM and QM pump have been tested in the full loop breadboard loop in Zhuhai (China). The mass flow and pressure head for nominal environmental conditions are shown below.

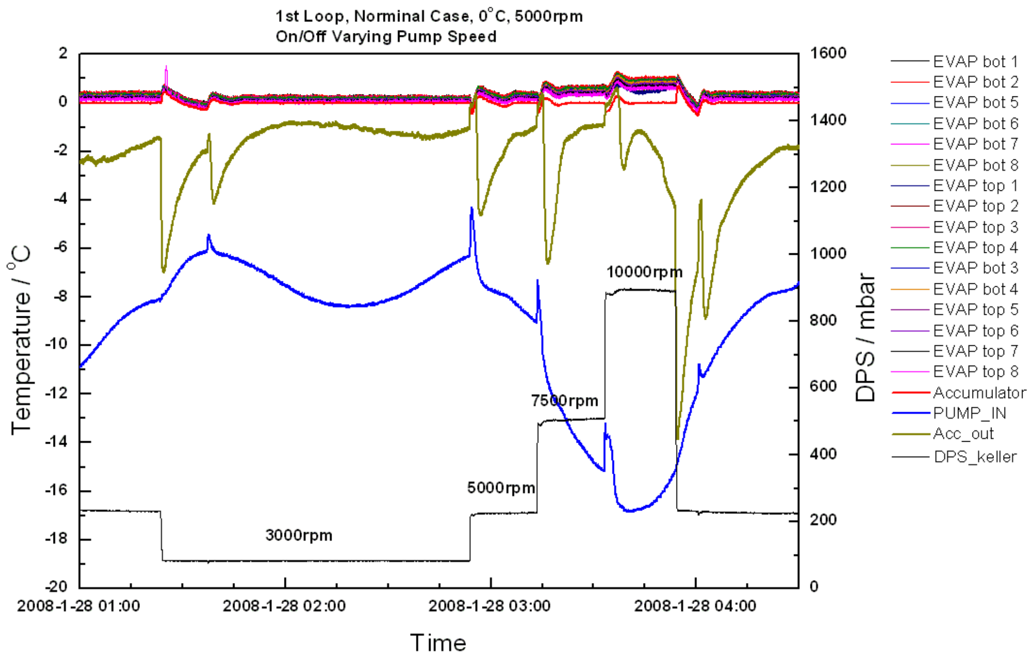


Figure 5-30: Pump performance in EM Primary Loop

More detailed pump requirements can be found in RD-23 and RD-24. Requirements verification can be found in the Acceptance Data Package of the TTCS pump.

5.6 Accumulator

The accumulator is the control room of the TTCS-loop. In the accumulator the evaporation temperature in the Tracker is set. Each loop is equipped with one accumulator. The set-point control components (Heaters, Peltiers) are redundant for each separate loop.

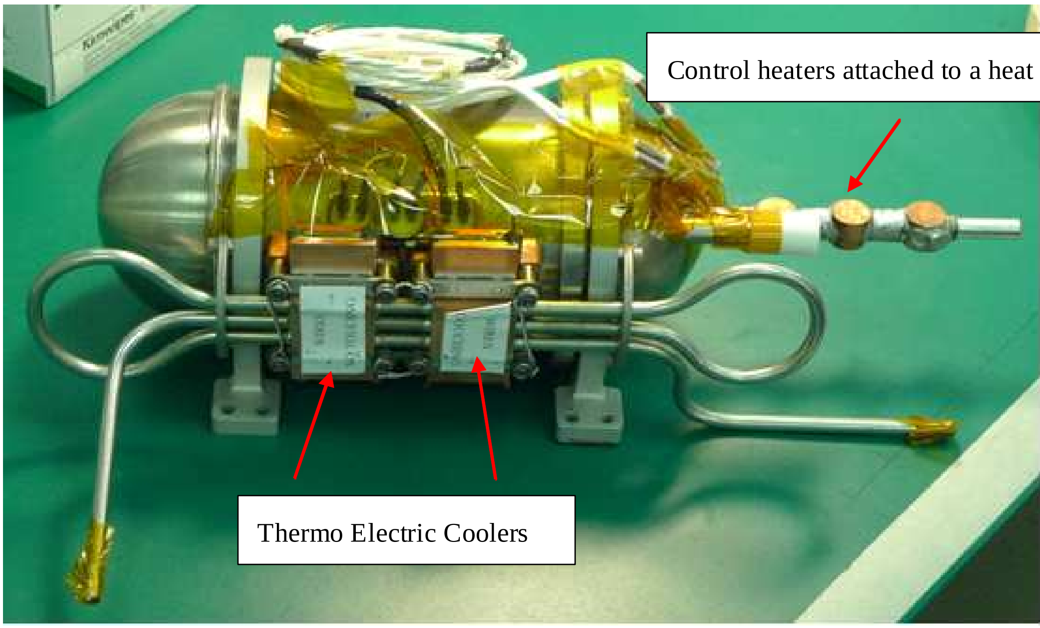


Figure 5-31: TTCS Accumulator with integrated Peltiers and heaters

Additional ground test heaters are located on the bottom side of the Primary accumulator. For the Secondary TTCB the ground control heaters are located on the top. This is due to the orientation of the TTCB's during the AMS02 system testing in the Large Space Simulator (LSS) in at ESA ESTEC Noordwijk (The Netherlands). The ground control heaters are used in hot conditions when the wick is not capable to re-wet the wick around the heat pipe.

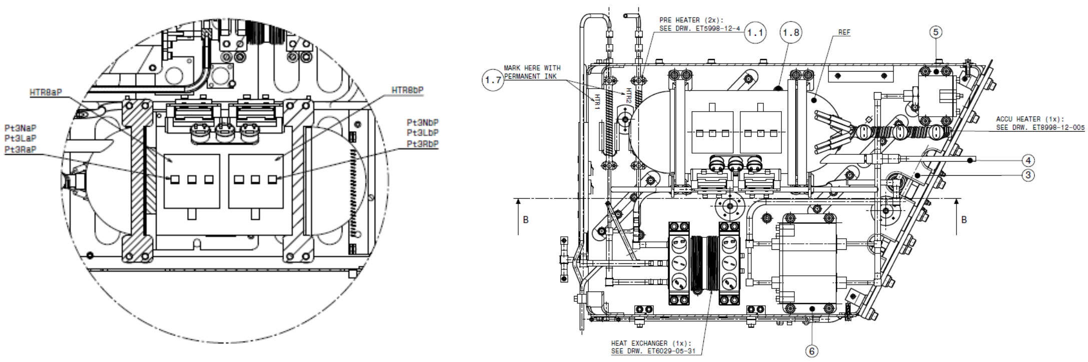


Figure 5-32: TTCS Accumulator Primary bottom view (left)
TTCS Accumulator Secondary top view (right)

5.6.1 Accumulator Functions

Component	Function
Accumulator	Regulate the evaporator temperature in the tracker Account for the expansion of the working fluid Account for the liquid front changes in the condenser during operation (incl. quality changes in condenser lines)
Accumulator Peltier elements	Regulate evaporation set-point in all operation modes (cooling)
Accumulator heaters	Regulate evaporation set-point in all operation modes (heating) Emergency accumulator heat-up in case liquid line temperature approaches saturation temperature (to avoid cavitation in pump)

5.6.2 Set-point control

The objective of the accumulator is to control the evaporator set-point and therefore the “cold plate’ temperature of the Tracker electronics. The principle is based on the property that a pressurised (closed) system with liquid and vapour has the same saturation temperature and pressure everywhere in the loop (neglecting flow pressure drop differences). In the TTCS accumulator vapour and liquid are present and is the main two-phase part in the loop. By changing the accumulator saturation temperature it is possible to change and set the evaporation temperature in the evaporator.

The actual set-point temperature control is performed by heating or cooling of the accumulator. The cooling will be performed by two Peltier elements Melcor CP 1.0-127-05 L 2 in series. The heating is done by wire heaters attached to a heat pipe heating the centre of the accumulator.

The control is described in section 7.

5.6.3 Account for volume changes due to temperature changes

Apart from the set-point control the accumulator also accounts for the volume changes (thermal expansion) of the working fluid (CO_2) average temperature. The CO_2 liquid density-changes from the lowest average (non-operating) temperature to the highest average (non-operating) temperature have to be taken care-off by the accumulator. At the lowest temperature the accumulator should still have liquid CO_2 in the accumulator and at the highest temperature the accumulator should be able to cope with the extra liquid volume CO_2.

5.6.4 Account for volume changes during operation

An accumulator in a two-phase system differs fundamentally from an accumulator in a single-phase system. A single-phase loop accumulator has to account only for the thermal expansion. In a two-phase other phenomena are present and have influence on the accumulator operation.

Most important phenomenon is the change in vapour volumes present in the condenser. As the condenser temperature change during orbit the so-called condenser front (i.e. the front were all fluid in the condensers is pure liquid) changes also. The changes in the condenser front immediately have effect on the accumulator level.

Increasing radiator temperatures/larger vapour volumes in condenser

In case of an increasing temperature in the condensers the amount of vapour in the condenser increases. As vapour density is smaller than liquid density the same mass in the loop takes more volume, resulting in a liquid flow from the loop to the accumulator. The accumulator should be able to account for this volume.

Decreasing radiator temperatures/smaller vapour volumes in condenser

In case of a decreasing temperature in the condensers the amount of vapour in the condenser decreases. This results in a liquid flow from the accumulator to the loop. The accumulator should be able to account for this volume.

Also the decreasing and increasing volumes in the accumulator cause fluid in the accumulator to condense and evaporate. The temperature control should be able to account for this changes.

5.6.5 Accumulator design and specifications

Although some Russian two-phase systems have flown, little experience is available with two-phase accumulators in space. The main design challenges of the required CO_2-two-phase system in space were:

- Keep liquid at the entrance of the accumulator to avoid vapour from the accumulator to enters the pump
- Keep liquid attached to the wall where controllers heat the accumulator (avoid dry-out of wick material)
- Pressure resistant upto the pressures present in the CO_2-systems 160 MDP

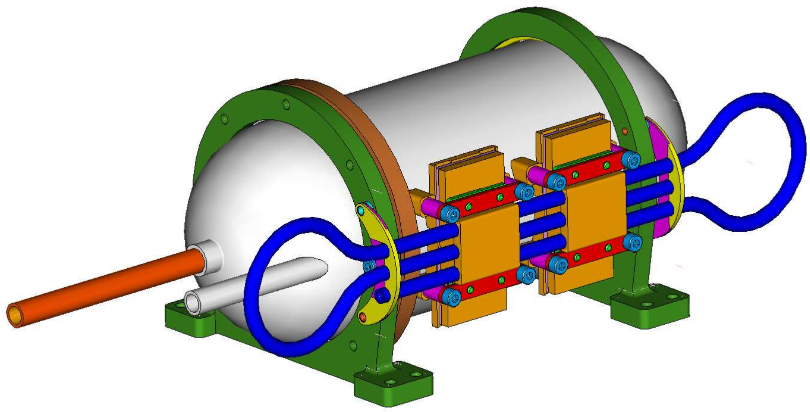


Figure 5-33: TTCS Accumulator assembly

Based on TTCS system design information NLR defined the accumulator size requirements and concept design (RD-25). The China Academy of Space Technology (CAST) translated the concept design in a detailed design. Development tests were defined in close co-operation between NLR, NASA and CAST. INFN made the bracket design and SYSU performed the thermal safety calculations as defined by NLR.

Liquid at the entrance of the accumulator

As the accumulator has to operate in space, one of the main challenges is to keep the liquid present at the connection with the liquid line. It has to be avoided that vapour CO_2 enters the loop as it will damage the pump. To keep the liquid "attached" to the entrance of the accumulator a wick structure is used around the liquid the entrance pipe. On top of that a fan structure is used. The fan structure contains enough liquid CO2 to provide the largest possible liquid request in case of a Tracker electronics shutdown. In that case all vapour in the evaporator condenses and additional liquid is needed to fill the gaps.

Figure 5-34: Liquid inlet pipe with mesh

Liquid attached to the accumulator wall

To be able to control the set-point in the accumulator heat must be exchanged with the liquid in the accumulator. It is therefore of vital importance that the liquid is attached to the wall in μ-g conditions to avoid dry-out. This design challenge is tackled by using a heat pipe to heat the internal CO_2 wick structure. By using a heat pipe no dry-out can occur as the heat provided to the heat pipe will condense on the coldest spots inside the accumulator. As soon as a part of the CO_2-wick will dry out no more heat (condenses) at that location of the heat pipe. Evaporated CO_2 is replenished by liquid from the surrounding wick.

High design pressures

A special CO_2-related design challenge is the relative high design pressure of CO_2. The accumulator structure has to deal with these pressures without loosing the connection between the wick structure and the container wall.

More detailed information on requirements and design can be found in RD-24 and RD-25.

5.7 Heat Exchanger

The heat exchanger is used to reduce the pre-heater power during nominal operation. The heat is exchanged between the exit and the inlet of the evaporator. The heat dissipated by the Tracker electronics is re-used for pre-heating in cold orbits. The maximum required pre-heater power is therefore reduced to 50 Watt (25 Watt per branch).

In Figure 5-35 the reduction of pre-heater of required pre-heater power is shown by introduction of a heat exchanger. The modelling is performed with a SINDA-FLUINT thermo-hydraulic model, calculating two-phase flow in the plumbing on one side and single phase flow at the other side. The periodic change in temperature is due to the environmental (orbital) heat flux boundary conditions. The simulation is performed with a low-efficiency heat exchanger and therefore only indicative for the relative reduction of power.

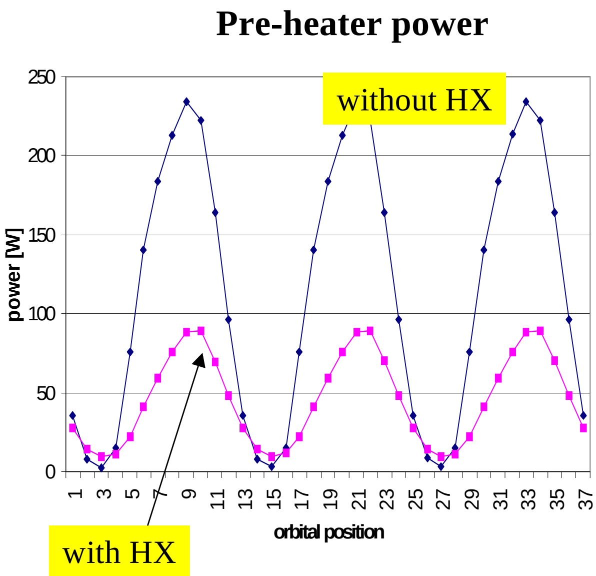


Figure 5-35: Pre-heater power with and without heat exchanger (modelled with low-efficiency heat exchanger)

Based on the simulations a heat exchanger was designed, build and tested in the NLR breadboard loop. The technical implementation is shown in Figure 5-36, a plate type heat exchanger with a cold passage for the subcooled inlet and one hot passage for the evaporator outlet. A plate heat exchanger is chosen for the high pressure design, the low pressure drop, and the leak tight design. The contribution of the heat exchanger to the overall system pressure head is negligible and in the order of 5 mbar at the two-phase side and 1 mbar at the liquid side.

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Figure 5-36: Heat Exchanger 2-phase flow path

The heat exchanger has 36 plates with 18 passages for two-phase flow and 18 passage for single-phase flow at the subcooled side. The flow directions are such that the two-phase flow enters from the top (resulting in a different orientation for Primary HX and Secondary HX).

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Figure 5-37: Heat Exchanger 2-phase flow path

The single phase flow path exits around the mantle of the stacked plates. After leaving the heat exchanger this flow will enter the evaporator.

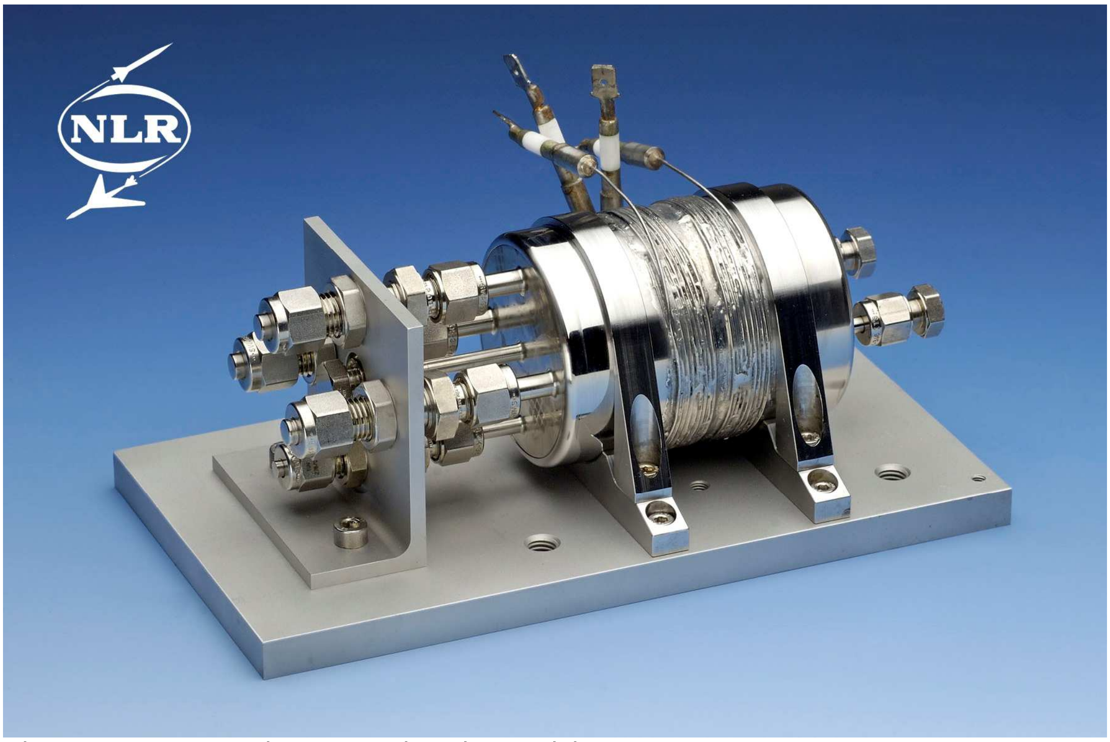


Figure 5-38: Heat Exchanger Engineering Model

Figure 5-39: Heat Exchanger Engineering Model details

5.7.1 Heat exchanger design

The main design challenges for the heat exchanger are:

- High pressure design (solved by choosing Inconel 625 as construction material)
- Leak tight design (all welded design)
- Operation in µ-g

For the latter the number of heat exchanger plates is over-dimensioned. The measured heat exchanger performance is excellent. This resulted in a reduction from the pre-heater power to almost zero. Only in extreme cold cases 16 Watt (2 x 8W) pre-heater power is needed. More information on the heat exchanger design can be found in RD-26.

5.8 Pre-heaters

The function of the pre-heaters is to heat the sub-cooled liquid to saturation temperature (i.e. set-point) before it enters the evaporator. Each evaporator branch is equipped with its own pre-heater (see Figure 5-1) to avoid phase-separation at the split-point to the evaporator branches. This design allows therefore ground testing in normal AMS-orientation. The pre-heaters wire heaters are redundant and soldered to the evaporator branch tubing on a small copper structure. The control is simple on/off. The maximum required pre-heater power is 8 Watt per evaporator branch.

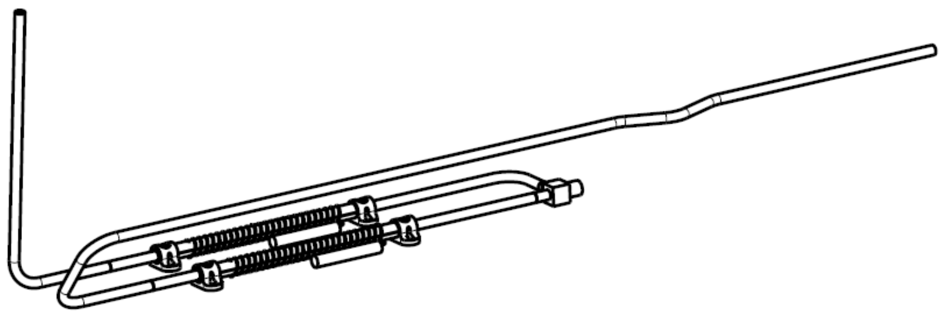


Figure 5-40: Pre-heater assembly

- Material: stainless steel.
- Outer diameter: 0.5 mm.
- Power supply: 28 V DC.

More details can be found in the TTCS heater document RD-4. The heater

5.8.1 Pre-heater design

The main design challenges for the pre-heaters are:

- Connection with the TTCS-tubing

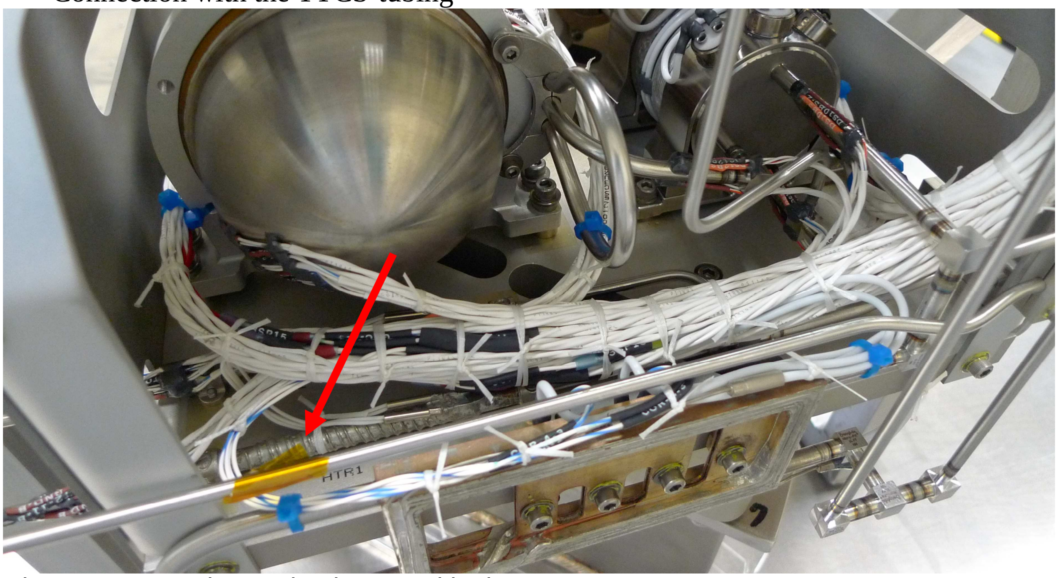


Figure 5-41: Pre-heater implemented in the TTCB-P

5.9 Start-up heaters

Next to the pre-heaters also start-up heaters are implemented in the design. Function of the start-up heaters is to heat the flow to the evaporators above –20 °C to avoid cooling the Tracker electronics during start-up in cold orbit conditions.

During start-up deeply cooled liquid (-40 °C) is pumped from the radiator to the Tracker. The start-up heater is able to lift the cold CO_2 to –20 °C. The start-up heater is controlled with a simple on/off control. The required start-up heater is calculated to be 50 Watt and is located on the mantle Heat Exchanger. This is possible because the liquid flow exits the heat exchanger along the mantle. The start-up wire heaters are soldered to the Heat Exchanger mantle and is protected by thermostats to avoid overheating and melting of the solder.

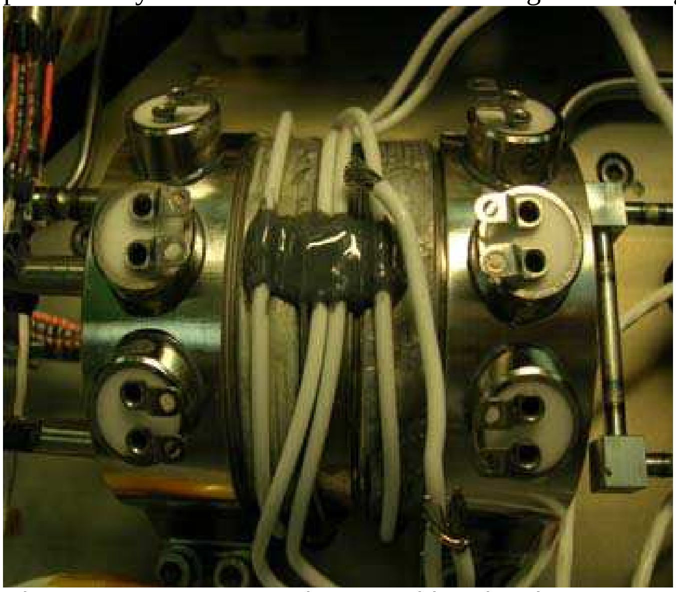


Figure 5-42: FM Start-up heater soldered to the HX

5.10 Cold Orbit heater

The cold orbit heater is introduced in the design to avoid freezing of the condensers in cold orbit. The Sinda-Fluint modelling showed a 60 Watt heater was provides enough power to avoid freezing (RD-13).

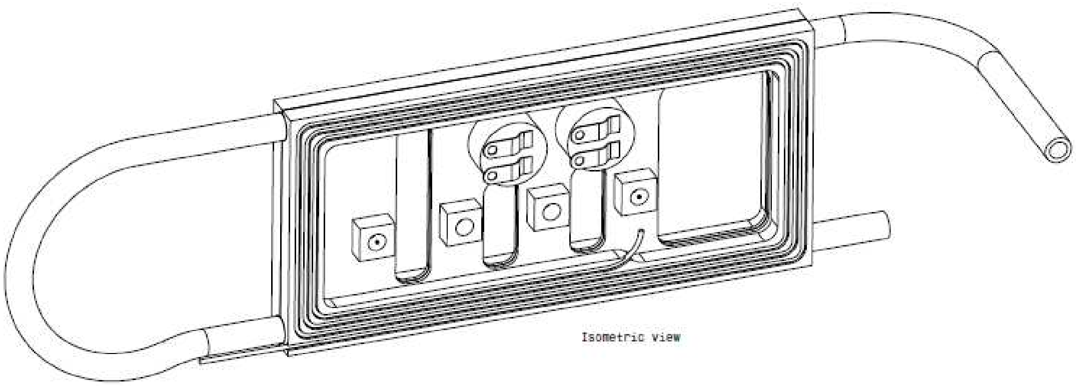


Figure 5-43: Cold orbit heater assembly

The cold orbit heater is a soldered design. A thermostat is implemented to avoid unnecessary overheating of the heater assembly.

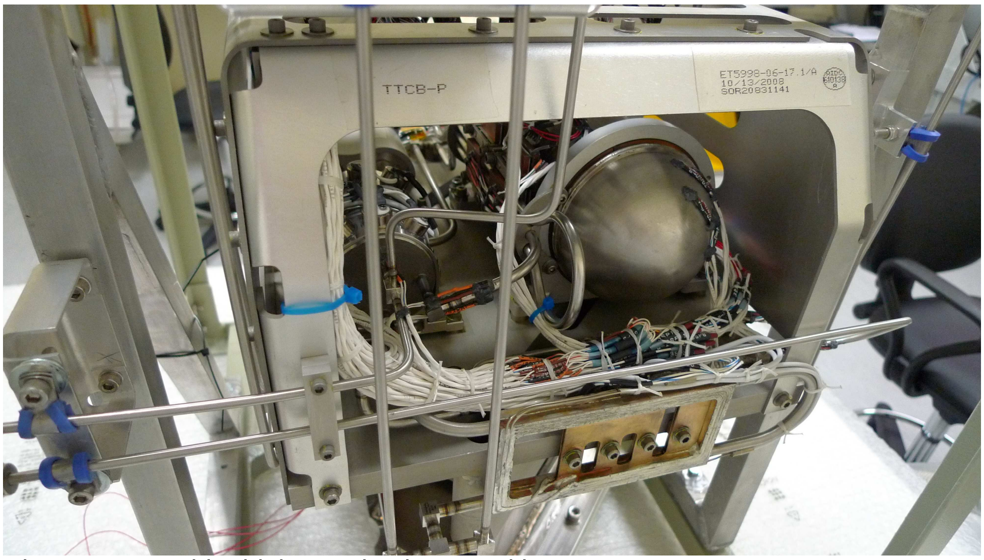


Figure 5-44: Cold orbit heater implemented in TTCB-P

5.11 Absolute pressure sensor

The function of the absolute pressure sensors is to monitor the TTCS system pressure. As the TTCS is a two-phase system the pressure is also a direct measurement of the saturation (set-point) temperature.

Specifications:

- Range: 0 - 100 bar.
- Accuracy: 0.5% FS.
- Total mass: < 400 g.
- Maximum dimensional envelope: h x w x b = 100 x 100 x 100 mm^3.
- Power consumption: < 1 W.
- Space qualified.

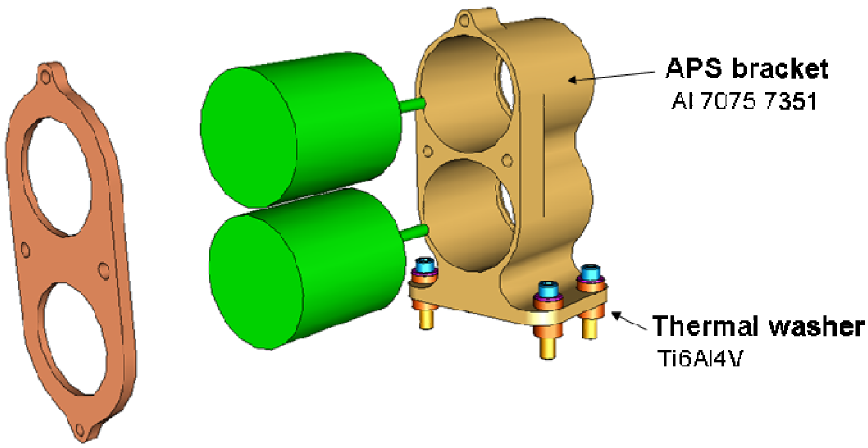


Figure 5-45: APS Assembly

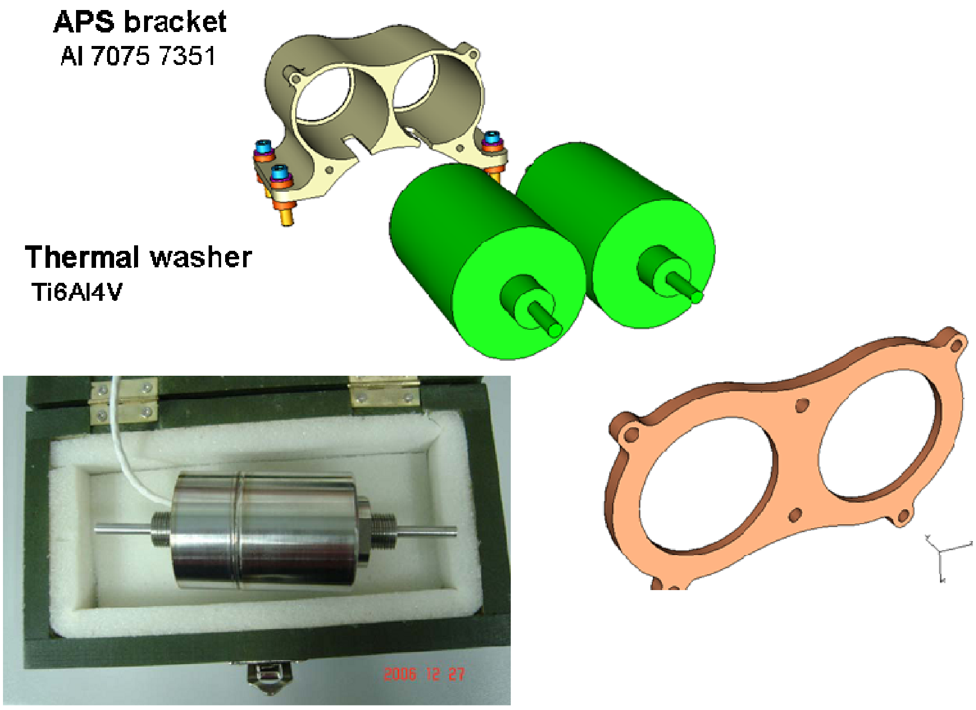
The APS is manufactured by CETC in China. The brackets are designed by INFN and NLR.

5.12 Differential Pressure Sensor

The function of the DPS is to monitor the pressure drop over the pump. This pressure drop monitors the pump health.

- Extreme low values will indicate dry-running (pumping vapour) or pump failure
- Extreme high values will indicate obstruction of the loop flow

The differential pressure also measures the loop mass flow. This value is not accurate as it is an indirect measurement and depends on the set-point temperature and the condenser temperature (environment). However terrestrial calibration of orbital conditions can give acceptable accurate results. The measured value for the mass flow will not be used in flow control, only as health indicator of the pump.



Specifications

- Range: 0 - 1000 mbar.
- Accuracy: 0.5% FS.
- Total mass: < 200 g.
- Maximum dimensional envelope: h x w x b = 100 x 100 x 100 mm^3.
- Power consumption: < 1 W.
- Space qualified.

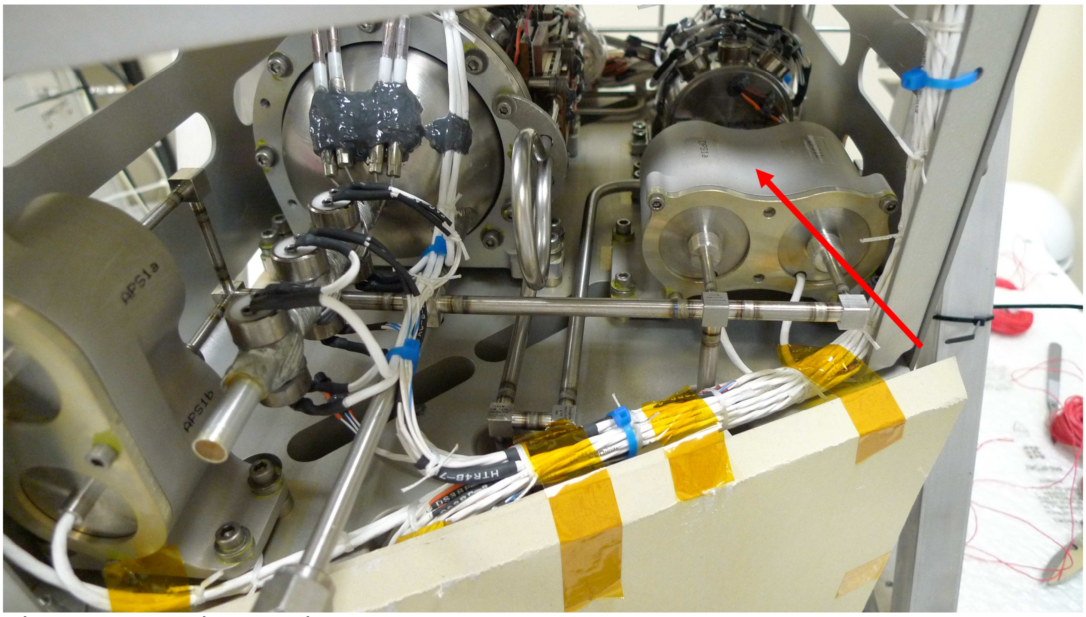


Figure 5-46: Implemented DPS

5.12.1 DPS design

The main design challenges for the DPS is:

- Low differential pressure at extreme high system pressure

5.13 Temperature sensors

The TTCS uses two types of temperature sensors:

- Dallas DS 1820 sensors.
- Pt1000's.

Dallas sensors are only used for monitoring. The Pt1000's are used for all low-level control options and for temperature monitoring on locations where the Dallas sensors are outside their temperature range.

5.14 Evaporator

In Figure 5-47 to Figure 5-49 and overview of the evaporator lay-out is shown. The inner diameter of the evaporator is 2.6 mm and the total length is 10 m.

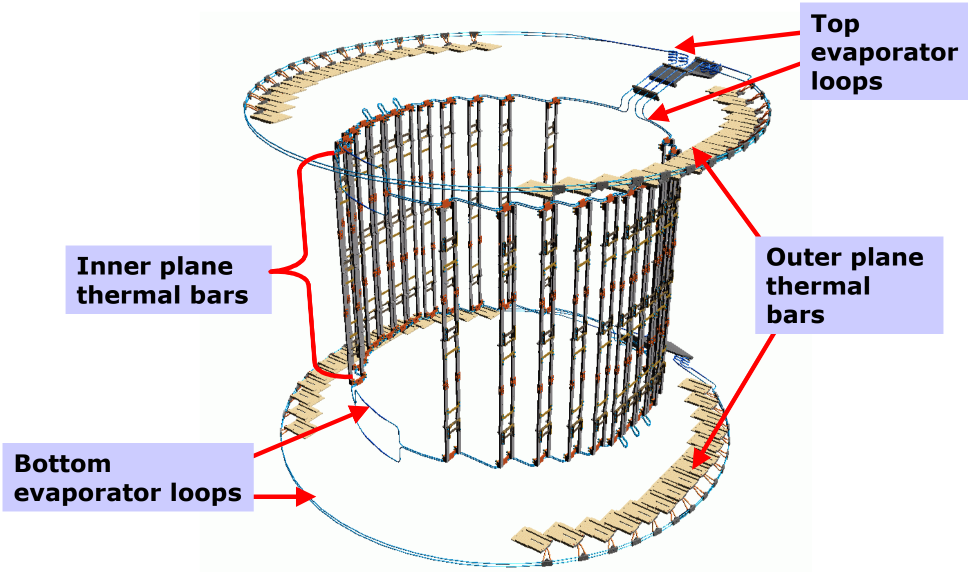


Figure 5-47: Evaporator lay-out with thermal bars

Figure 5-48: Inner evaporator ring prototype

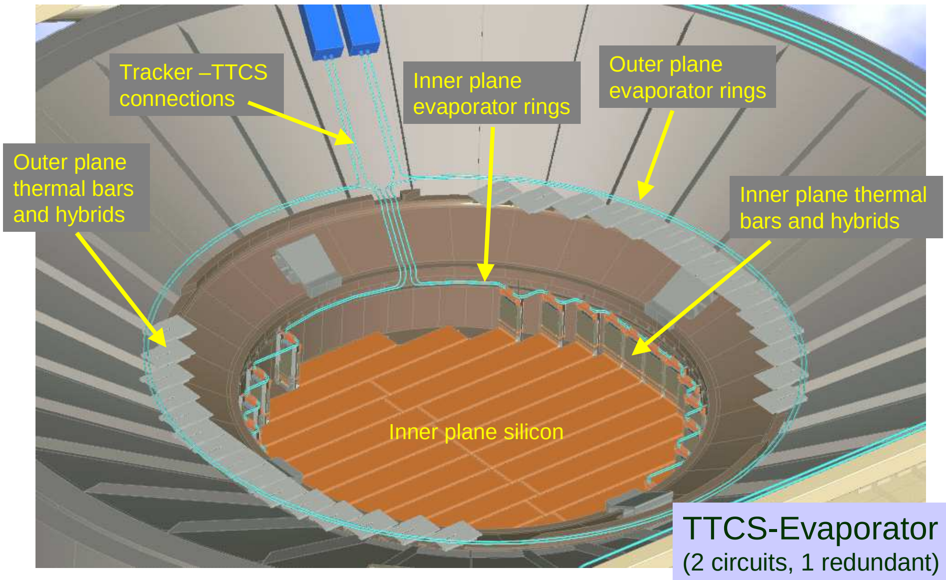


Figure 5-49: Top evaporator

Heat collected at the inner tracker planes is transported by thermal bars to the top and bottom evaporator ring. In Figure 5-48 the tube lay-out detail of the inner ring is presented, showing the complex distribution of the tracker front-end electronics.

5.14.1 Evaporator design and manufacturing

The main design challenges for the evaporator are:

- Limited volume (small diameter, small thickness piping)
- Welding of evaporator rings (performed by an orbital welding procedure)

5.15 Condenser

The main function of the condensers is to dump the collected heat to the Tracker RAM and WAKE radiator.

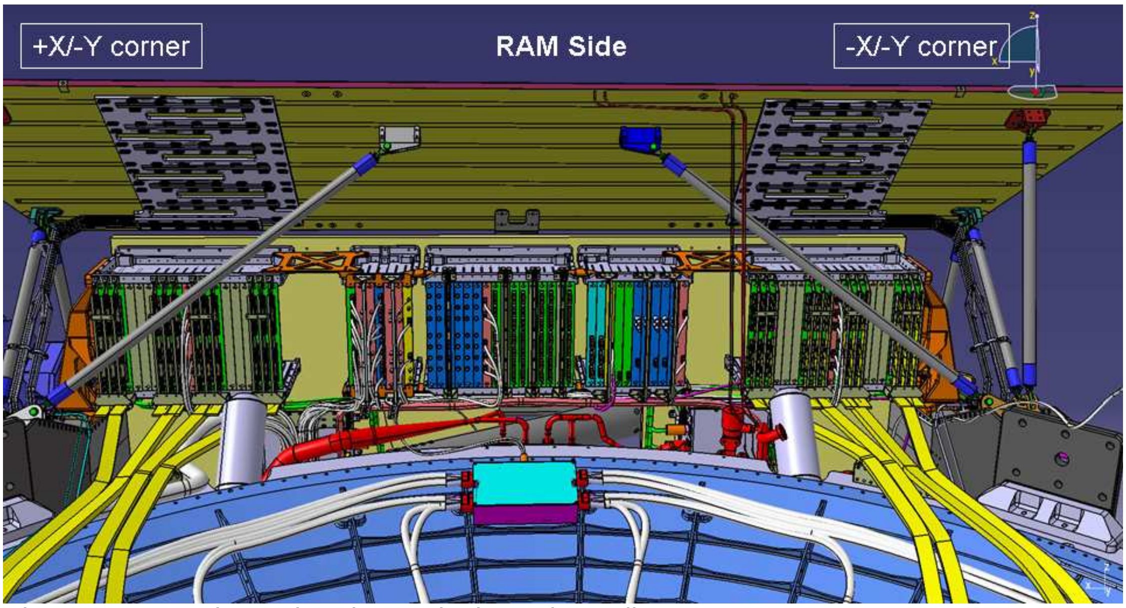


Figure 5-50: Condenser location on the heat pipe radiators

The vapour will condense at the set-point temperature. When all vapour is condensed, the liquid will be sub-cooled below the saturation point (set-point). For pump safe operation a minimum sub-cooling of 5 °C is required. Each loop has two parallel condensers, one on the WAKE Tracker radiator and one on the RAM Tracker radiator. The location of the condensers on the heat-pipe type radiators is shown in Figure 5-50. The condensers are attached to the heat pipes. The heat pipes will distribute the heat further over the radiator in axial direction. A detailed drawing of the radiator interface is shown in Figure 5-51.

5.15.1 Design drivers

Due to the fact that CO2 can freeze and the radiator can become extreme cold (-120 C) the condenser design is not straightforward. The main design drivers are:

- Freeze proof design in cold orbit in accordance with NASA safety requirements for pressurised systems
- Cover a temperature range of -120 ºC to +65 ºC (critical for connection between Inconel tubes and aluminium base plate)
- Heat transfer capability in hot orbit
- Small to moderate pressure drop through the condenser
- Fit on the Wake and RAM tracker radiators

5.15.2 Design rationale heat transfer

In order to optimise the heat transfer capability to the radiator the design needs look after:

- Sufficient heat transfer area
- Good thermal coupling between the condenser tubing and the radiator

The sufficient heat transfer area is realised by a number of parallel tubes. Total 7 parallel condenser tubes can be accommodated on each HP flange. The area can further be maximised by the length along the HP flanges.
The thermal coupling between the fluid and the radiator plate is built up of several contributions.
Main design challenge is to connect the Inconel condenser pipes to the aluminium base plate. The connection will be performed with MASTERBOND EP21TDC-2LO glue in order to cope with the CTE-difference between Inconel and aluminium. In order to show the feasibility of the connection with glue CTE testing was performed. NLR designed a test sample and test set-up and showed the feasibility.

5.16 Design rationale freezing

The major design challenge was to cope with the so-called freezing problem. In fact the freezing problem is a melting problem. In case of a full AMS power shutdown the temperature of the condenser section drops below the freezing temperature of CO_2 (-55 ºC) downto minimum temperatures downto -120 ºC. In case the condenser heats up in an un-controlled manner liquid CO_2 can be present in enclosures surrounded by solid parts. Rising temperatures can then induce high pressures. This was a potential safety risk.

The design solution chosen for this problem is as follows.

- Freezing is allowed in condenser part of the tubing
- This condenser part will be freeze proof upto maximum melting temperatures induced by the environment (-5 ºC) (RD-28)
- It will be shown that the rest of the TTCS tubing will not be below the freezing point (RD-14) of CO2 during the mission. So the normal TTCS MDP is valid in all sections except the condenser section.

In RD-7 the AMSTR-NLR-TN-039-Issue03 “TTCS Condenser Freezing Test Report” it is shown that the MDP (Maximum Design Pressure) in the condenser tube is 3000 bar based on a maximum condenser temperature of -5 º C. It was also shown that a small diameter Inconel 718 tube (din = 1.0mm, dout = 3.0 mm) can shown to withstand this pressure using a safety factor of 1.5 for yield and 4.0 for burst. Based on this results a detailed design was made.

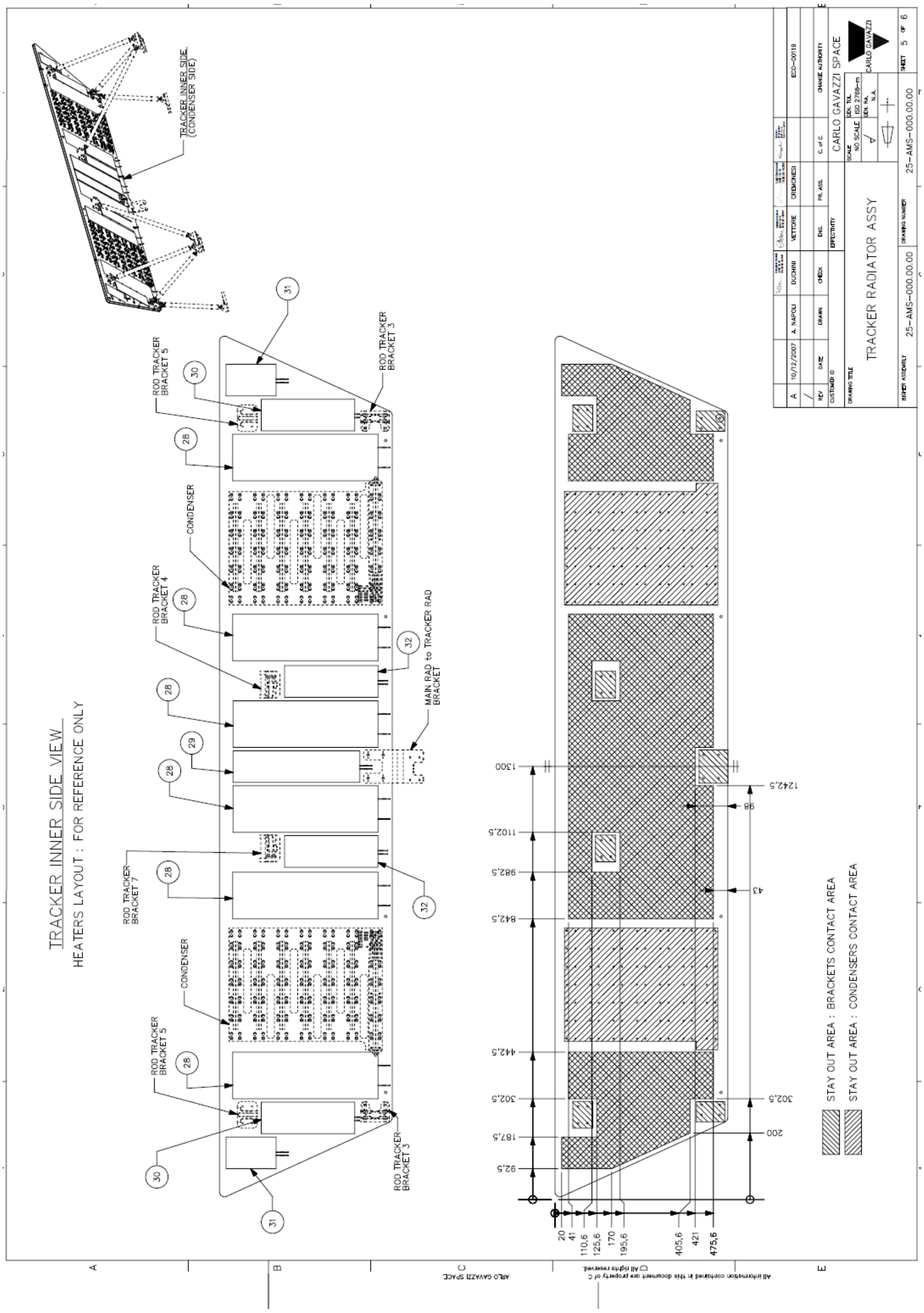


Figure 5-51: Detailed radiator drawing with condenser locations shown

5.16.1 Condenser Design

Finally Inconel hardened 718 tubing was chosen with Do = 3.15±0.05 mm, Di = 1±0.2 mm which can withstand the 3000 bar MDP. The design consists of seven parallel condenser tubes meandering over a base plate. The base plate is bolted with 98 bolts to the Tracker radiator.

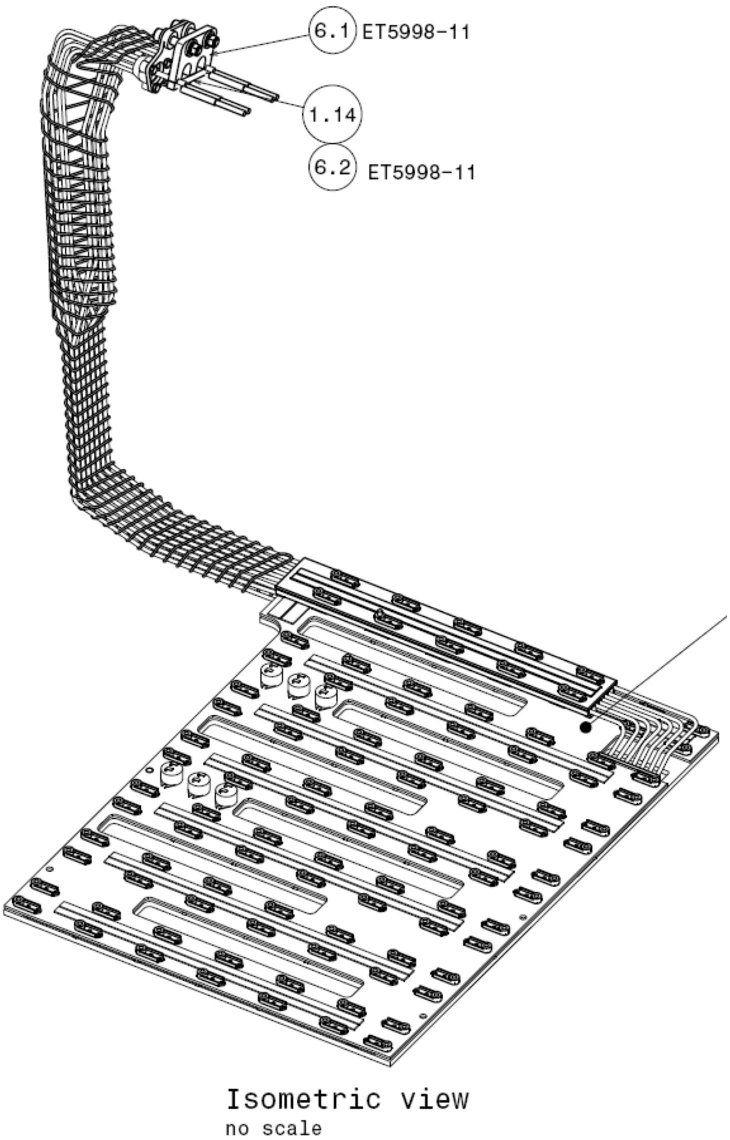


Figure 5-52: Condenser assembly drawing

The condenser manifolds will finally merge the 7 capillary tubes to one TTCS transport tube. The location of the manifolds is located on the upper vacuum case joints as indicated in ***Figure 5-53***. The manifold is a brazed connection and is brazed in one go with the hardening heat treatment of the Inconel 718.

The manifold also includes a simple wire mesh filter to avoid blockage of the small condenser tubes by contamination.

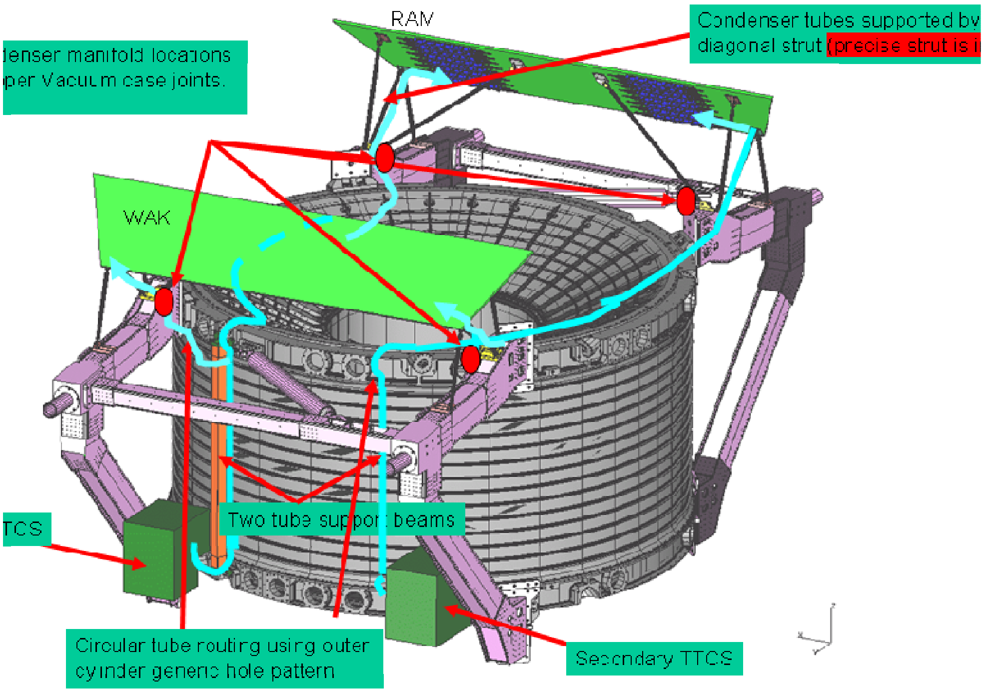


Figure 5-53: Location of the condenser manifolds on AMS02

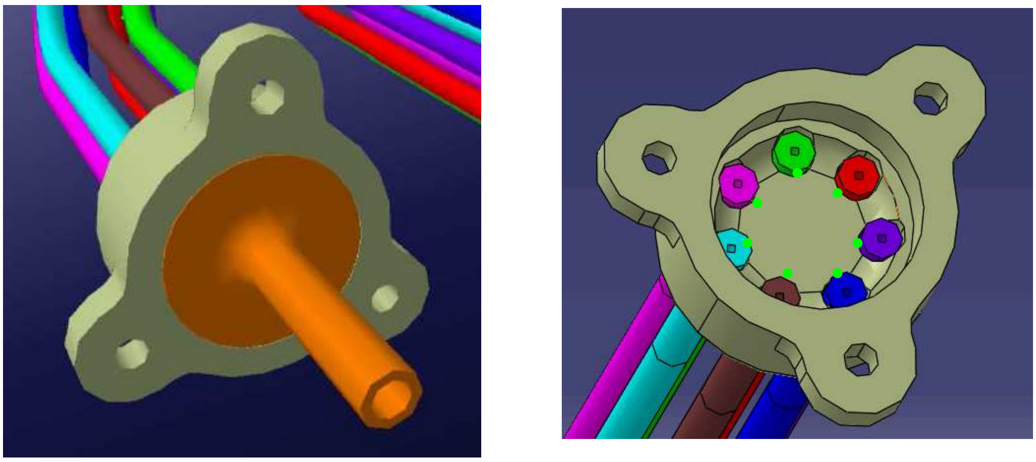


Figure 5-54: Condenser manifold detail

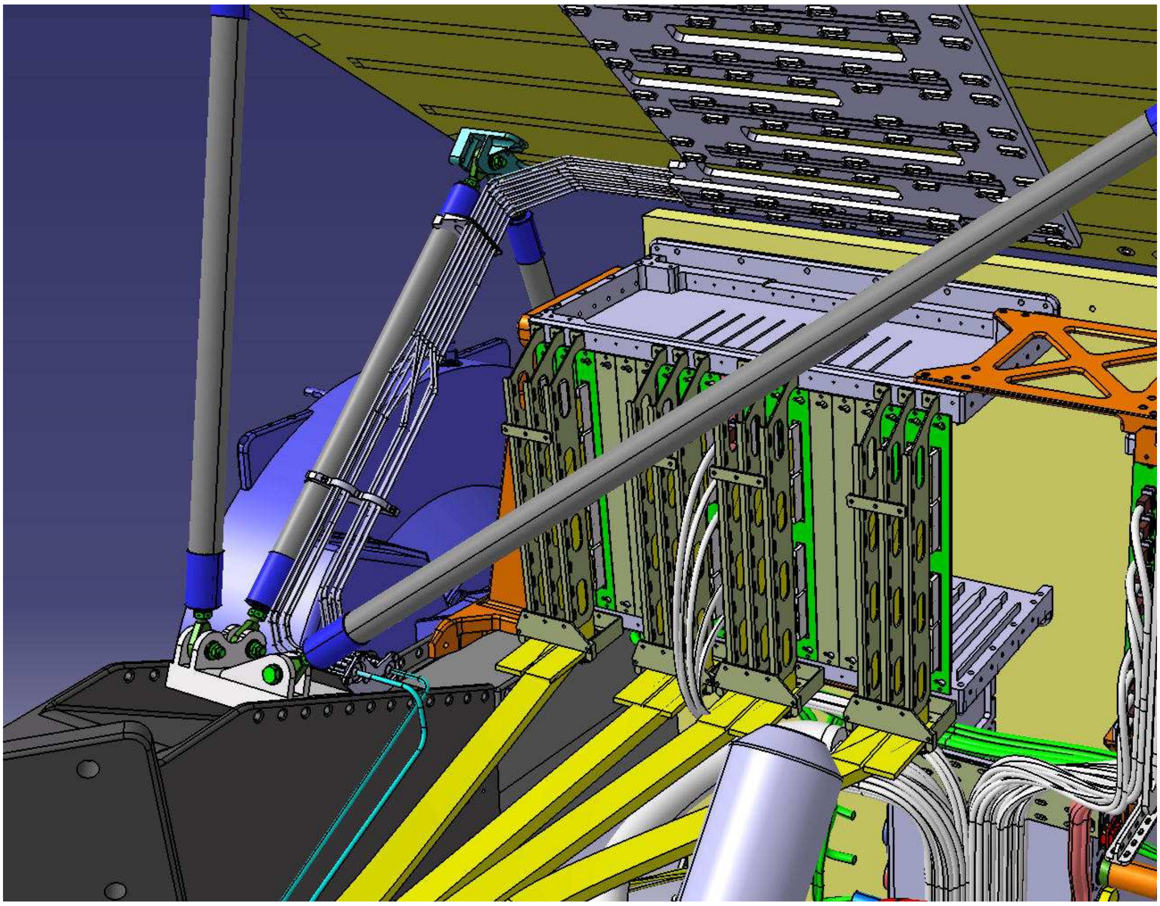


Figure 5-55: Condenser manifold locations detail (picture F. Cadoux)

The 7 capillary tubes are routed along the (in ***Figure 5-53*** and ***Figure 5-55***) indicated radiator struts. The total condenser tube length is approximately 3.3 m

- Condenser tube length embedded in the condenser plate is 2.49 m.
- Length from the manifold to the base plate “entrance” is estimated on 0.45 m
- Total 3.4 m

The condenser manufacturing has been performed at AIDC Taiwan based on a NLR design and with NLR technical support and all under the local supervision of INFN (E. Laudi).

The main steps in manufacturing are:

- Tube cleaning
- Manifold brazing and Inconel strain hardening
- Proof pressure testing and He-leak testing
- Several gluing steps

Figure 5-56: Condenser gluing

The final condenser will be attached to the Tracker radiator on a Sifgraflex interface sheet.

5.16.2 Liquid line health heaters

Around the inlet and outlet tubes of the condenser the so-called liquid line health heaters are wrapped. These heaters are used to defrost the liquid inlet and outlet after a AMS02 power down. In that case the condensers are frozen and part of the inlet and outlets too. To avoid liquid is created in the condenser plates right between the frozen inlet and outlet the liquid health heaters are switched on first. This will melt the CO2. After this the Tracker radiator heaters can be switched on.

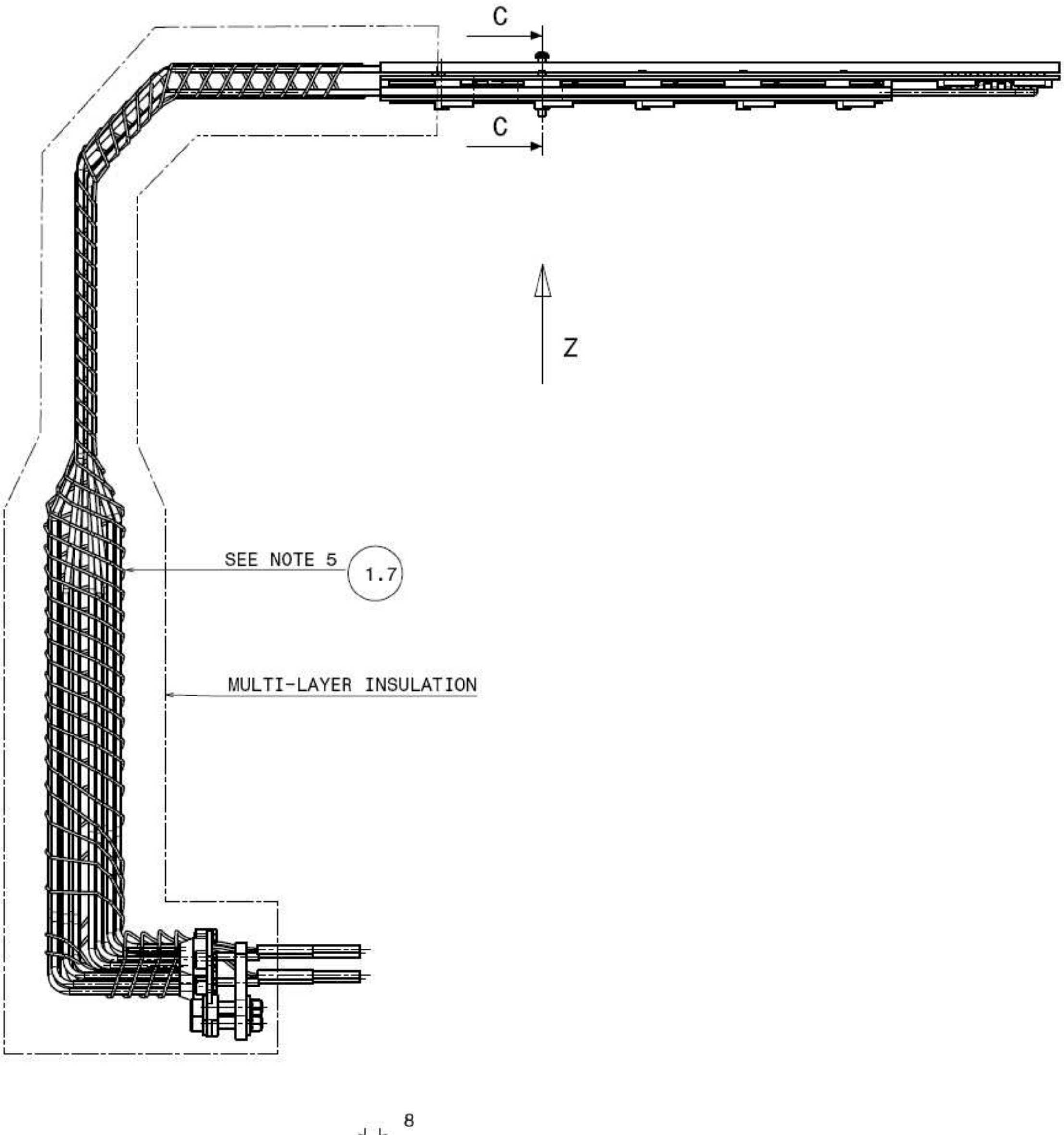


Figure 5-57: Liquid line health heaters wrapped around the condenser inlet and outlet

Detailed information on the TTCS heater design can be found in the TTCS heater specification RD-04.

6 TTCS Operation and on-board software functions

6.1 TTCS Operation, Monitoring and Control

In this chapter the TTCS operation of the AMS02 Tracker Thermal Control System is described. The TTCS system comprises:

- **Ground Segment (TTCS-GS)** including the TTCS Ground Monitoring & Control System
- **Space Segment (TTCS-SS)** including a limited amount of TTCS software located in the JDMC and the TTCE firmware and associated on-board hardware.

An overview of the TTCS-SS and the TTCS Ground M&C System is given in Figure 6-1 below.

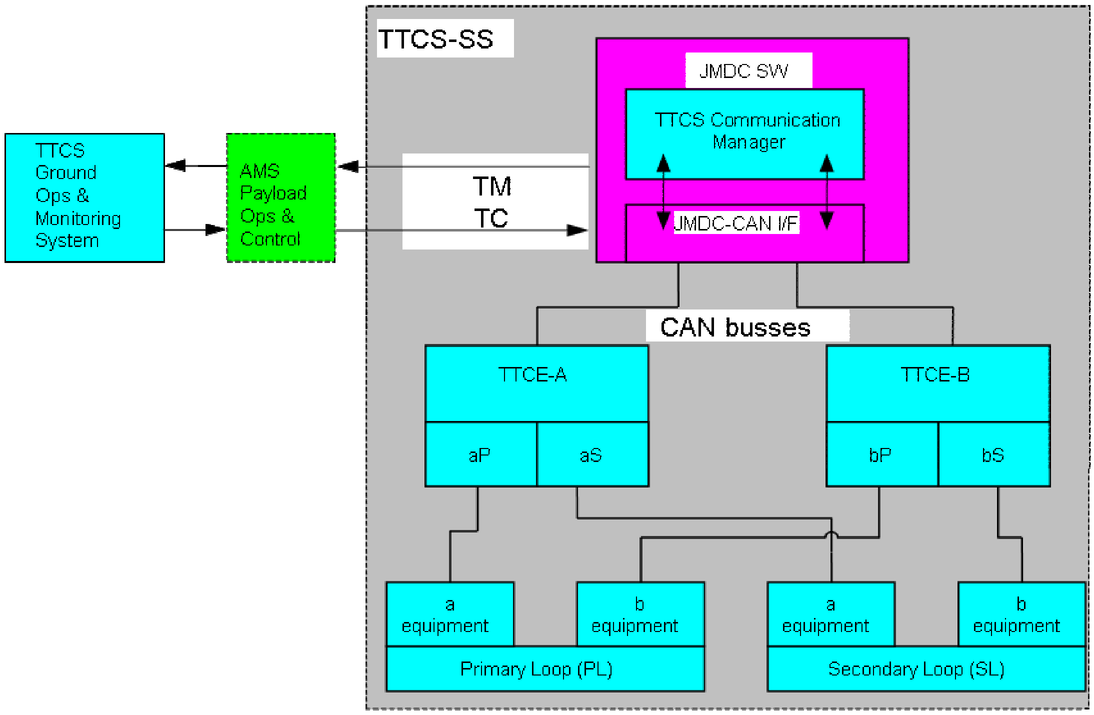


Figure 6-1: Overview of TTCS Space Segment and TTCS Ground M&C System.

The TTCS-SS comprises the TTCE A and B and the primary loop and its A and B equipment, the secondary loop and its A and B equipment, and the TTCS related software running in the JMDC.

The current baseline for TTCS operation, monitoring and control is:

- TTCS-SS is operated during real-time ground contact via (ground-operator) telecommands to the TTCS Communication Manager located in the JMDC.
- The TTCS-SS operation and control is monitored on-ground via telemetry
- TTCS control algorithms for on-board control loops are located in the TTCEs (only very limited higher level control o/b)

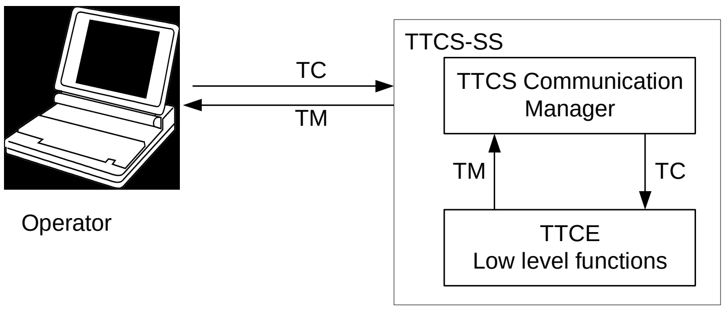


Figure 6-2 Hierarchical software layering for TTCS-SS operation

The TTCS operation and control via on-board software is as follows:

- High-level SW in JMDC in the TTCS Communication Manager: TM/TC management, Mode Monitoring, 5% of all health guards (requiring other then TTCE data), command and data I/F with TTCEs
- Low-level SW in TTCEs: data acquisition, control loop execution, 95% of all health guards, command and (tm)data, IF with TTCE-Manager

The envisaged TTCS on-board interfaces and data flow in the JMDC is shown below:

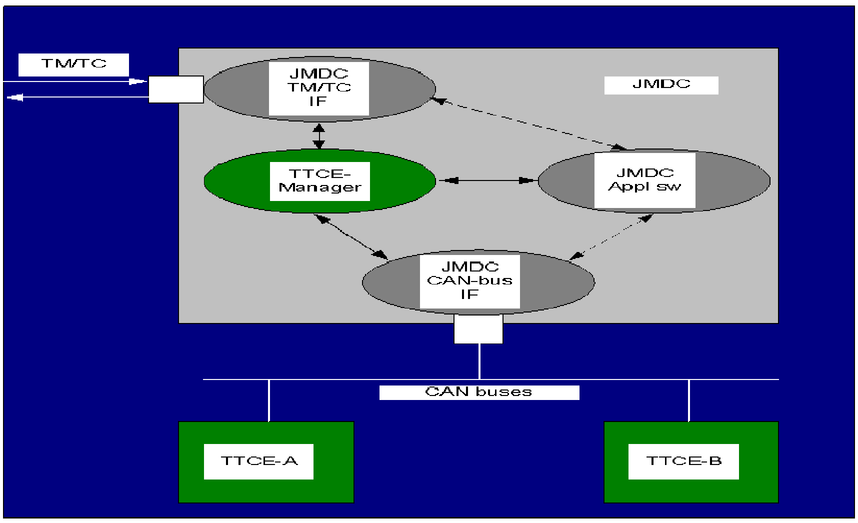


Figure 6-3: TTCS On-board data flow

The TTCS Communication Manager and the TTCEs contain two types of functions:

- Fixed functions: functions that are always executing in a way depending on their fixed logic
- Commandable functions: functions that can be enabled/disabled, switched or configured by telecommand. The status of commandable functions determine the command-status of the TTCE-Manager and the TTCEs.

The Status (incl. health guards trigger status) is kept in status words.

6.1.1 TTCE-Manager functions in JMDC

The TTCE-Manager has the following fixed functions:

- TTCS-SS Operational Mode status monitoring
- TC reception I/F with JMDC SW
- (tele-)command management
- (tele-)command I/F with TTCEs via JMDC CAN communication IF
- (tm-) data polling I/F with TTCEs via JMDC CAN communication. IF)
- TM data I/F with JMDC SW
- Health-flag I/F with JMDC SW
- Health guards co-ordination between TTCEs if both TTCE-A and -B are "On". (optional TBD/TBC)

The TTCE-Manager Commandable functions are:

- Control loops: None
- TTCE-Manager located Health guards: run always, fixed rate, but can be enabled/disabled
- (tm) Data Polling Tables: can be loaded and enabled/disabled

The TTCE-manager functionality is very limited. The main operation decisions are made by the ground operator. System health is mainly looked after by health guards implemented in the embedded TTCE S/W and will be send to ground by a health bit.

6.1.2 TTCE S/W functions

The TTCEs fixed S/W functions are limited to command and data interface functions via the CAN bus:

- The TTCE(s) sw handles commands from the TTCE-Manager.
- The TTCE(s) sw respond(s) to the (TM) data polling requests from the TTCE-Manager.

TTCEs Commandable S/W functions comprise:

- Control loops (enable-/disable)
- Health guards (enable-/disable)
- Data acquisition and (tm) data collection functions
- Direct control by telecommand:
    - Accumulator Heaters/TECs PWM, Preheaters on/off, Start-up heaters on/off, Cold Orbit heaters on/off, Liquid line health heaters on/off.

Control Loops; run always, at fixed rate, but can be enabled/disabled. Only two PWM controls are present in the TTCE:

- Accumulator control loops (a, b, PL, SL)
- Pump speed control loops (a, b, PL, SL)

Health guards run always but can be enabled/disabled.

TTCE Sensor Data acquisition and (tm) data collection run always data-sets to be acquired/collected can be set by telecommand.

6.2 TTCS Status monitoring

The current baseline is monitor TTCS status and TTCS command statuses by status words.

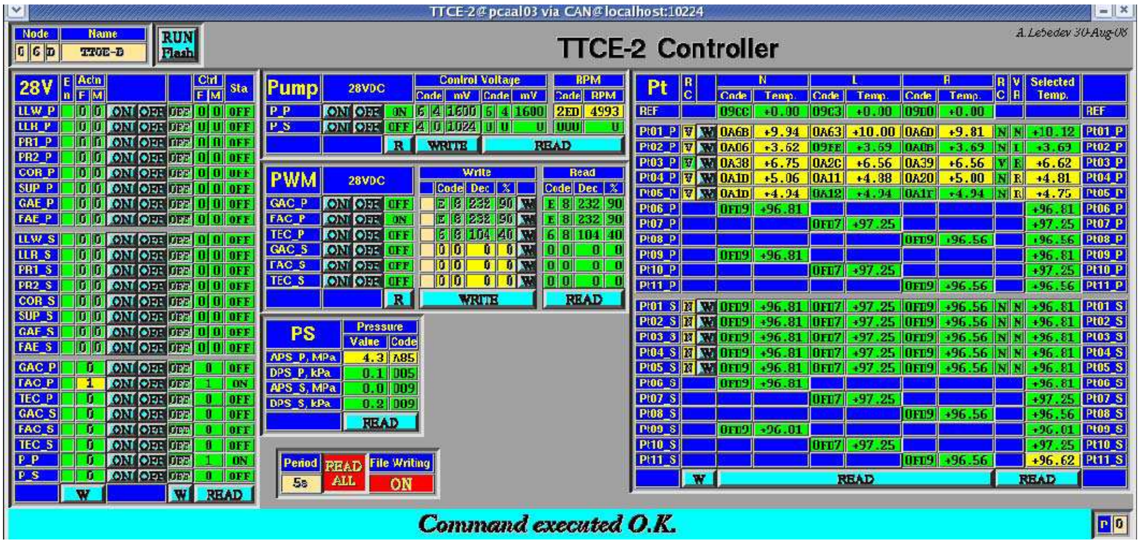
The TTCE-manager will have status indications (not yet implemented) for:

- TTCE-Manager PL & SL Health guards On/Off status words
- Data Polling Tables (DPT) status word
- Health guards trigger status words

The TTCE embedded S/W delivers the following status indications:

- TTCS Status words
    - active TTCE
    - active cooling loop
- TTCE-A & B PL & SL Control loops On/Off status
- TTCE-A & B PL & SL Direct Control status
- TTCE-A & B PL & SL Health guards On/Off status
- TTCE-A & B PL & SL active data acquisition/collection sets
- Health guards trigger status

The implementation of the TTCE embedded status words is shown below:



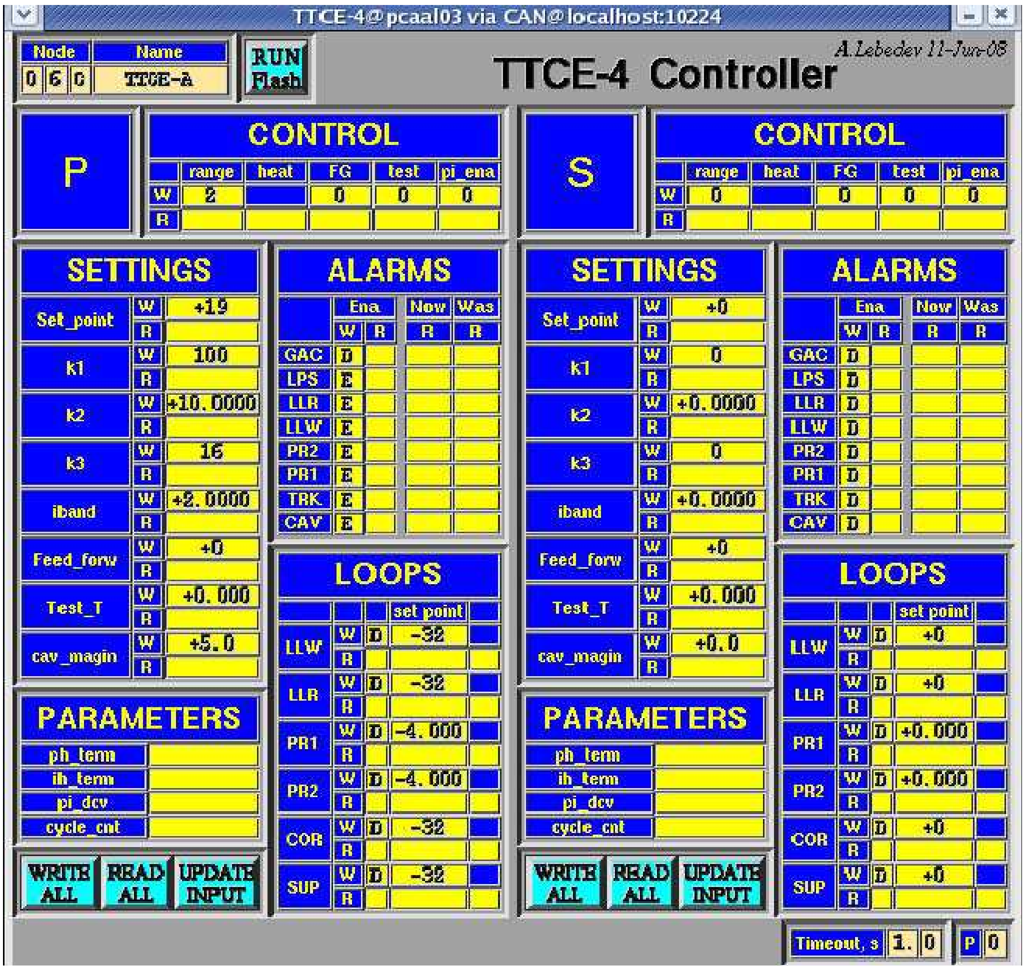


Figure 6-4: TTCS Control Interface

6.3 Operational modes definition in ground control

The baseline design is that the TTCS-SS state is not known by the TTCE-manager. The TTCE-manager only communicates (continuously) the status to ground.

Due to the open and flexible set-up of the in-orbit communication and control by ground commands it is proposed to define clear operational modes before sending commands up. By checking the status of the TTCS-SS the actual state can be verified.

In the chosen redundancy concept for the TTCS, see Figure 6-5, the TTCE-A interfaces with the A (primary) equipment of the Primary and Secondary loop. TTCE-B interfaces with the B (secondary) equipment of the Primary and Secondary loop. Both TTCE-A and TTCE-B can operate the Primary and the Secondary Loop. The Primary Loop can be operated from TTCE-A, but if Primary Loop A-equipment fails, it can also be operated from TTCE-B.
Even Primary loop operation with a combination of A and B equipment with TTCE-A and B shall be possible. The same holds for the Secondary loop.

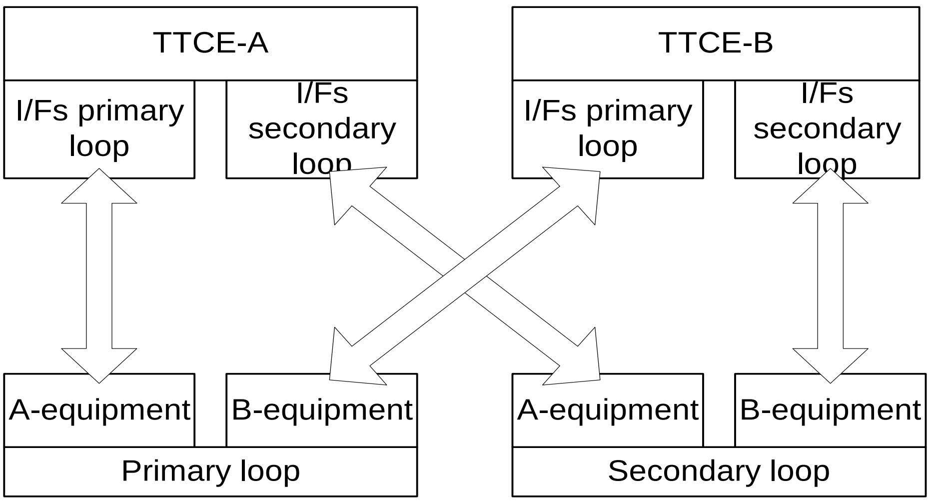


Figure 6-5: Operation of primary (A) and secondary (B) equipment on Primary and Secondary Loop

6.3.1 TTCS-SS State diagram.

The TTCS-SS operational modes can be represented in a finite state machine. States and sub-states are defined in a hierarchical manner: Starting at the highest level of the state machine, sub-states are defined as specialisations of the more general parent state.

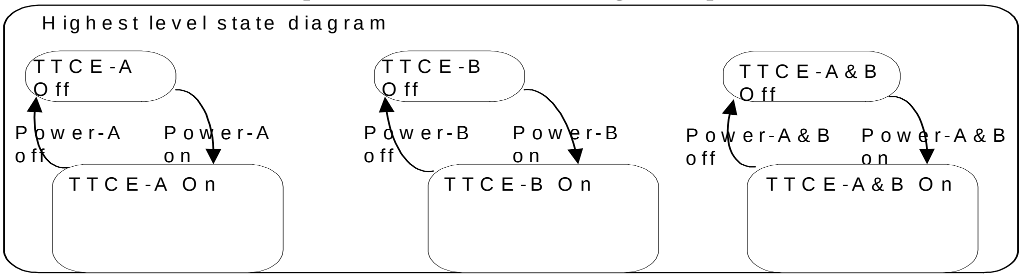


Figure 6-6 Highest level TTCS-SS state diagram

The TTCS-SS states are defined from the view of the Ground Operator. In Figure 6-6 the highest level state diagram of the TTCS-SS is drawn. At the highest level of the TTCS-SS state diagram, it is distinguished whether: TTCE-A or TTCE-B or TTCE-A&B are On or Off.

It is tacitly assumed that the JMDC is On and the TTCE-SS Manager is On. The Off states are of no further interest.

- The TTCE-A On state is achieved by powering up the TTCE-A
- The TTCE-B On state is achieved by powering up the TTCE-B
- The TTCE-A&B On state is achieved by powering up TTCE-A and TTCE-B

For the Primary and Secondary Loop the same high level state diagram applies.

6.3.2 Operational modes

From the highest level state to the next lowest level diagrams the TTCE "On" states are more detailed into their sub-states..

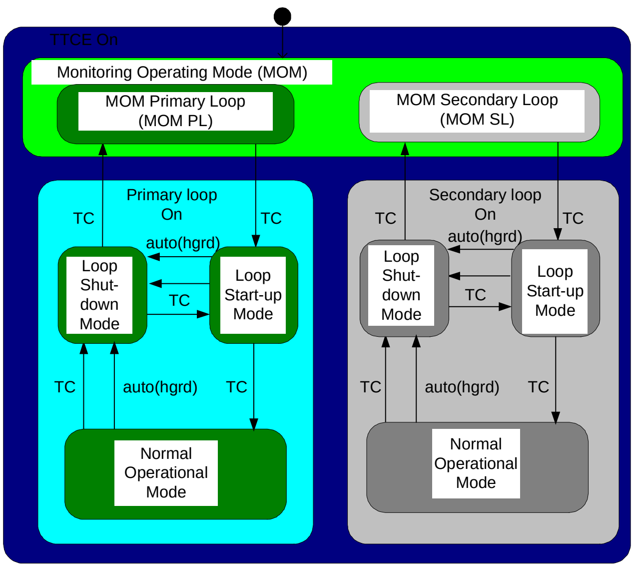


Figure 6-7 Overview operational modes state diagram for active loop, TTCE-A or TTCE-B "On"

These sub-states are called modes in the sequel, as they constitute the operational modes of the TTCS-SS the operator experiences. This lower level state diagram is shown in Figure 6-7. The operational modes are those states of the TTCS-SS in which the TTCS-SS is operated, autonomously by the TTCS-SS Manager or from the Ground. All operational modes are sub-states of the TTCE On-state. More information on the operational modes and scenarios will be condensed in AMSTR-NLR-TN-021-iss02-draft “AMS02 Tracker Thermal Control System TTCS Operational modes and scenarios”.

7 TTCS Electronics and Control functions

The TTCS electronics is fully redundant for primary and secondary loop. For the loop hardware, pure cold redundancy is foreseen. The AMS Tracker Thermal Control System electronics can be divided into the following elements:

TTCS Flight system

- Control Electronics (TTCE) including Power Distribution (TTPD)
- Mission Computer (JMDC) with TTCS Communication Manager
- Ground Support Equipment (EGSE)

7.1 Block Diagram

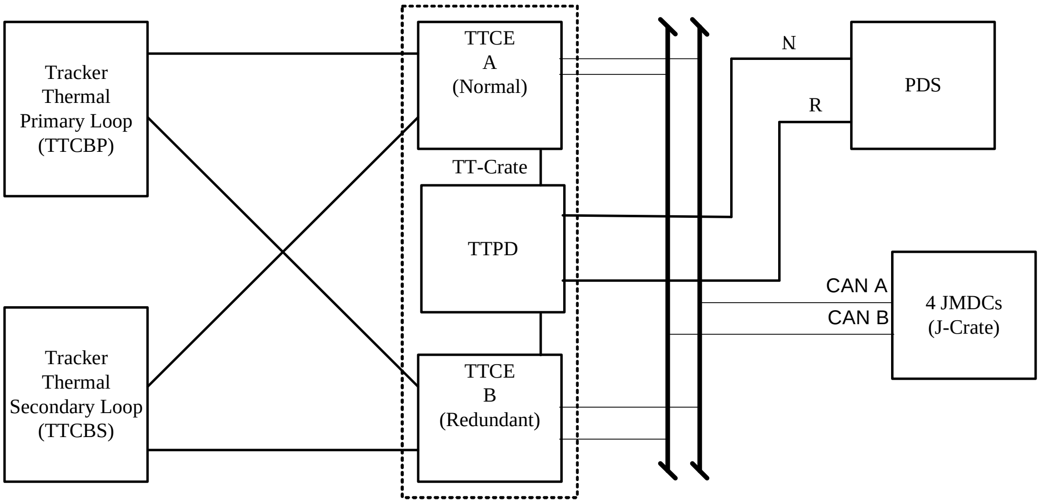


Figure 7-1: TTCS electronics block diagram

7.2 Control loops

The TTCS actuators are controlled in a two stage control loop:

1. High level command & control (limited)
2. Low level control

7.2.1 High level control

The high-level control will be an application on the JMDC. The high level control has the following control allocated functional requirements

- Pump set point control
- Temperature set point and set-point change control
    - Accumulator temperature

The pump speed is controlled at low level (see next section). However set-point changes can only be performed at high-level. The high-level control loops determines the set point temperatures and pump speed **changes**.

Also the **changes in the control parameters** of low-level controls (e.g. pre-heater control, accumulator control) can only be changed at high level.

7.2.2 Low level control

The low level controls in the TTCS are

1. on/off control loops:
    - Condenser liquid lines health heaters RAM and WAKE,
    - Preheaters 1 and 2
    - Start-up heater 5
    - Cold orbit heater 10

The inputs into the heaters are either from

- CLOSED_LOOP: 28V on/off by control algorithm
- MANUAL: 28 V on/off by manual (i.e. by telecommand)

2. PI control accumulator
    - Accumulator PI control loop comprises heater for heating and Peltier element (TEC) for cooling. The heaters are actuated by a filtered PWM output (0 ... + 28 V) for heating The TECs are actuated by a filtered PWM output (0 ...+ 28 V) for cooling. Furthermore the accumulator is equipped with ground test heater.

The inputs into the heaters are either from

- CLOSED_LOOP: input into PWMs by PI control algorithm
- MANUAL: input into PWMs set manually (i.e. by telecommand)

3. Pump speed control
    - The pump is controlled by a local rpm-controller located at the pump. The pump controller also gives a feedback rpm-signal to the TTCE.

      The TTCE can change the pump speed by putting an analogue signal to the pump controller.
    - Pump Speed Control (PDT)

      Settings: pump speed

      Inputs: rpm-value to pump (analogue signal)

      Outputs: rpm to TTCE (for monitoring only, no feedback)

Remark: Details of the pump control can be found in the controller specification: PW82520 Radiation tolerant 3-phase DC motor torque controller from DDC.

7.3 TTCS Health guards

Apart from the component control also **TTCS health guards** are implemented to secure health (electronics within temperature limits, no cavitation in pump etc) of the system. The on-board implemented TTCS health guards will be limited to the detection of potentially hazardous situations requiring fast on-board response, due to incorrect functioning of the TTCS.

The general purpose of the health guards is to signal unforeseen behaviour of the TTCS to the ground and to take action and bring the TTTCS to a healthier operating mode.

The TTCS on-board health guards will not comprise failure detection, i.e. detection of which failed component(s) might have led to the unsafe situation.

Failure detection and recovery will be a task of the Ground Monitoring & Control system. The Ground M&C system will serve to process telemetry and to monitor the TTCS-SS operational behaviour and to do failure detection.

The following health guards are foreseen:

7.3.1 High-level TTCS health guards

Health guards are present at low-level and high-level. The guards operating at high level (JMDC) are:

- **Overall Tracker Electronics high and low temperature health guard**
  Purpose: To provide an overall independent protection of the Tracker Electronics for
  - too high temperatures, and
  - too low temperatures,

  outside the operational range of the Tracker Electronics, through switching off the Tracker Electronics
- **JMDC-TTCE communication outage health guard (in TTCE-Manager)**
  Purpose: Protect the Tracker Electronics for possibly hazardous malfunctioning of the TTCS, by switching-off the Tracker Electronics after a TTCE-JMDC communication outage of more than TTCS_JMDC_Com_out_duration_limit = +10 (TBC) samples
- **Condensers freezing health guard**
  Purpose: Prevent freezing of the condensers, by monitoring relevant temperature sensors (at condenser outlets and/or (better) on radiators, and alerting the TTCE-Manager to command the PDS to power-on the 120 V survival heaters.

7.3.2 Low level health guards

Currently the following health guards are foreseen:

Health guard number	**Full Health guard name**
hgrd 1.	Level_1 Pump inlet subcooling margin health guard
hgrd 2.	Level_2 Pump inlet subcooling margin health guard
hgrd 3.	Working temperature out of Tracker range health guard
hgrd 4.	Preheaters temperature too high health guard
hgrd 5.	Condenser lines health heaters RAM temperature too high health guard
hgrd 6.	Condenser lines health heaters WAKE temperature too high health guard
hgrd 7.	Low pump speed health guard
hgrd 8.	Accu ground test accu heaters temperatures too High health guard

Table 7-1: List of low-level health guards

Health guard 1

Level_1 Pump inlet subcooling margin_Y:

Hazard

The liquid temperature at the pump inlet may come close to the saturation temperature belonging to the currently set system pressure/temperature, such that, if the inlet temperature would further increase,, cavitation at the pump inlet would occur.

Purpose of the health guard

The purpose of this health guard is to signal this situation by setting the hgrd1 health bit to Not_OK and to let the health guard action execution increase the accumulator setpoint. The accumulator temperature setpoint is increased, such that the saturation pressure is increased and cavitation is prevented.

Health guard 2

Level_2 Pump inlet subcooling margin_Y:

Hazard

For some unknown reason (e.g. heaters are inadvetently on due to manual operation error, or due to a hot environment the return liquid temperature increases faster than the accumulator setpoint) the pump inlet temperature comes close to saturation (< level 1 subcooling margin) such that cavitation at the pump inlet occurs.

Purpose of the healthguard

The purpose of this health guard is to signal this situation via the health bit and to let the healthguard action execution disable the follwing heaters, start-up heaters, cold orbit heaters, preheaters and condenser lines health heaters.

It has been decided recently that the pump will not be switched-off by this healthguard, in this situation. This could be done by ground command if the situation persists.

Healthguard 3

Working temperature out of Tracker survival range:

Hazard

1. At start-up the liquid flowing through the evaporators may be too cold for the tracker. If this is the case the start-up heaters and the pre-heater on/off control loops will be active. This mechanism might fail for some reason or initially might not immediately be capable to achieve the minimum survival temperature of the Tracker Electronics (-20 °C).
2. The accumulator temperature may become too high e.g. because of an accumulator control error, leading to a too high evaporator temperature and higher than the upper Tracker Electronics survival temperature (+ 20 °C).

Purpose of this health guard

This health guard health bit will indicate if the liquid flowing through the evaporator is out of the Tracker Electronics survival temperature range or not.

Healthguard 4

Preheaters temperatures too high_Y

Hazard

The temperature at the preheaters is too high ((much) higher than saturation), e.g. because there is no liquid flow.

Purpose of health guard

Indication of the preheater temp is too high via health bit and to let the health guard action execution disable the preheaters.

Healthguard 5

Condenser lines RAM health heaters temperature too high

Hazard

The temperature of the condenser lines health heaters RAM becomes too high.

Purpose of this health guard

Signal the too high temp situation via the health bit and to let the health guard action execution disable the condenser lines health heaters RAM.

Healthguard 6

Condenser lines WAKE health heaters temperature too high

Hazard

The temperature of the condenser lines health heaters WAKE becomes too high.

Purpose of this health guard

Signal this situation via the health bit and to let the health guard action execution disable the condenser lines health heaters WAKE.

Healthguard 7

Low pump speed healthguard:

Hazard

The TECs dump their heat in the liquid lines, which might lead to local overheating or boiling if there is no or little flow. This has occurred during breadboard tests and should be prevented by health guards.

Also preheaters, start-up heaters and cold orbit heaters shall be disabled when there is no or little flow

If preheaters, start-up heaters or cold orbit heaters on/off control loops are in CLOSED_LOOP while there is low or no pump flow, the on/off control loops can not keep the temperatures locally at the setpoint as the used temperature sensors are not located near the heaters and the on/off control loops hence can only function when there is sufficient flow

Purpose of this health guard

Signal that the pump speed is low via the health bit and to let the health guard action execution disable operation of TECs, start-up heaters, pre-heaters and cold orbit heaters if the pump speed is below a certain value.

Healthguard 8

Accu ground test heaters temperatures too high_Y

In addition to the above health guards, there is an additional safeguard which is only useful during the use of the ground testing heaters.

Hazard

For ground testing the accumulator is heated by ground test heaters mounted on the accumulator body and not by the heaters on the heat pipe.

Temperature at the location of the ground test heaters becomes too high.

Purpose of this safeguard

To signal this situation via the health bit and to safeguard the system for too high temperatures and pressures, by letting the health guard action execution disable the ground test heaters.

More information on the low-level health guards can be found in the TTCE software user requirements document RD-28.

The high-level health guards S/W and the ground monitoring S/W to define/detect the TTCS-SS state and a S/W manual for in-orbit operation is still to be further developed.

8 TTCS Development Philosophy

For the development of a fully compliant TTCS with the system requirements, the following Model Philosophy is proposed (see Figure 6-8-1). For cost reduction the Breadboard Models (BBM) and Engineering Models (EM) and the Qualification Models (QM) and Flight Spares (FS) have been combined into on model.

- Breadboard Model (BBM) / Engineering Model (EM)
- Qualification Model (QM)/Flight Spare (FS)
- Flight Model (FM)

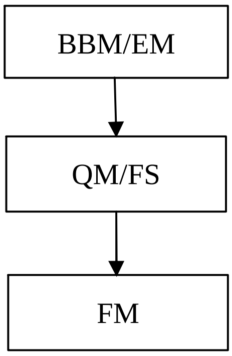


Figure 6-8-1: AMS TTCS Model Philosophy

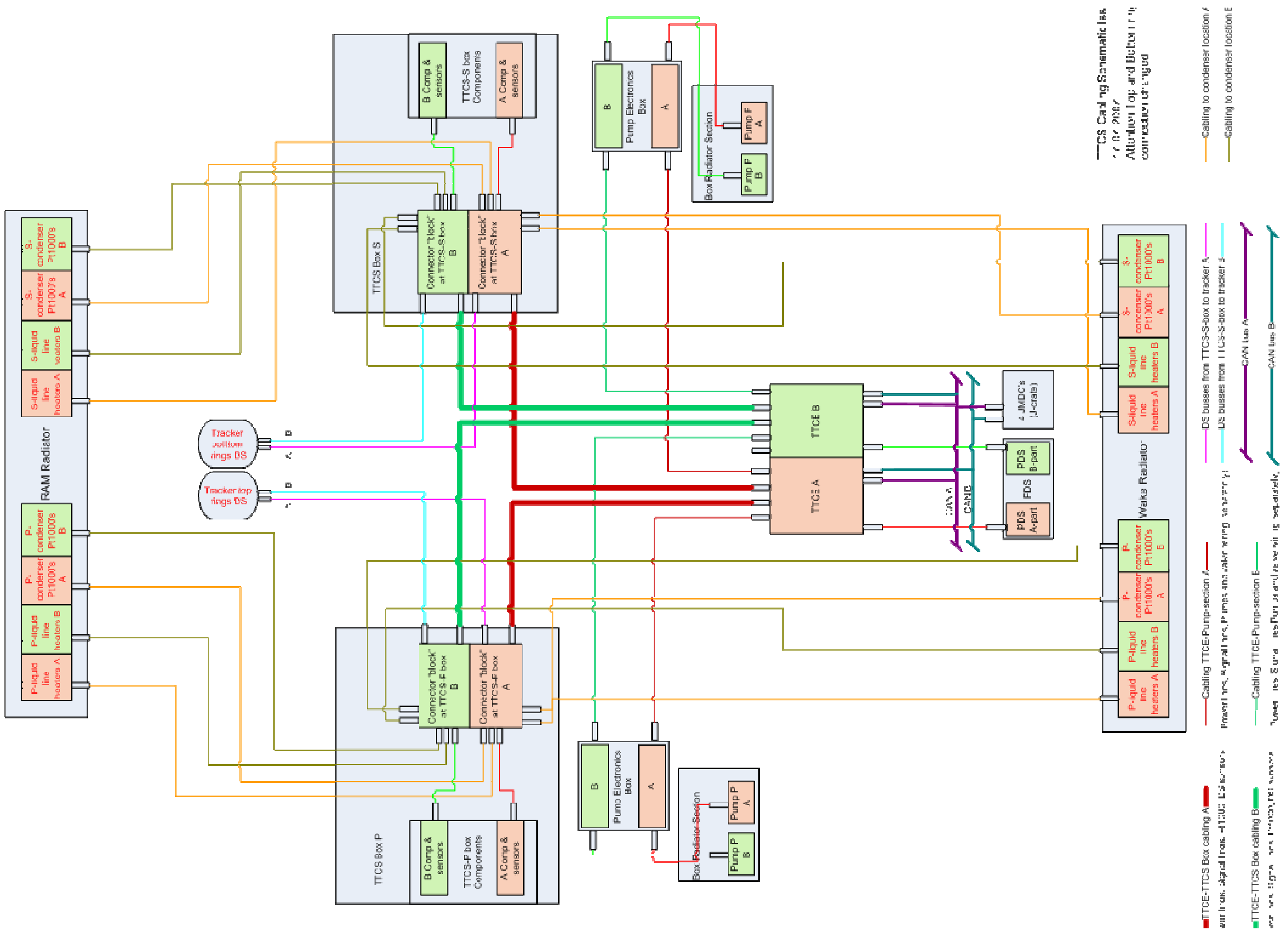
When the performance tests on one of the EM (sub)systems are completed the manufacturing of the Qualification Model (QM/FS) will start. The QM/FS is fully similar to the Flight Model (FM) and will be subjected to a qualification programme (EMC, Vibration & Shock, Thermal Vacuum). The QM/FS subsystems will be stored as Flight Spare. After successful qualification of the QM/FS the Flight Model manufacturing will be started. The FM (sub)systems are subjected to a functional check prior to integration in the AMS overall system.

8.1.1 Model Philosophy on subsystem and component level

	NLR		SYSU		SYSU/NLR		
System level		**EM**	**QM**	**FS**	**FM**	**Resp.**	**Remarks**
TTCS (complete system)		½	-	-	1	NLR	
(Sub)-System		**EM**	**QM**	**FS**	**FM**	**Resp.**	**Remarks**
TTCS-P Box		1	1	= QM	1	SYS	
TTCS-S Box		1	-	-	1	SYS	
Evaporator subsystem		½	½	-	1	NIKHEF	
Condensers		1	1	= QM	4	NLR	
TTCE		1	1	1	1	AMS02	
Component		**EM**	**QM**	**FS**	**FM**	**Resp.**	**Remarks**
Pump		1	1	1	4	NLR/SYS	
Accumulator		1	1	= QM	2	SYS/NLR	
Heat Exchanger		1	1	=QM	2	NLR/SYS	
Absolute Pressure Sensors		2	2	=QM	4	NLR/SYS	
Differential Pressure Sensor		2	2	=QM	4	NLR/SYS	
Pre-heaters		4	4	2	8	NLR/SYS	
Start-up heaters		-	2	= QM	4	NLR/SYS	
Cold orbit heaters		-	2	=QM	4	NLR/SYS	
Liquid line health heaters		-	2	= QM	8	NLR/AIDC	
Dallas Temperature Sensors		-	42	32	84	SYS	Divided over Tracker, box
Pt1000 Temperature Sensors Control		-	30	15	60	SYS	Control Pt 1000's
Pt1000 Temperature Sensors Monitoring		-	-	15	24	SYSU	Incl. Additional radiator Pt1000's

Table 6-2: Number of items under test for each model (the italic red number indicate if QM parts will be used as FS)

Appendix I: TTCS Cabling Schematics



Detailed cabling information see RD-30

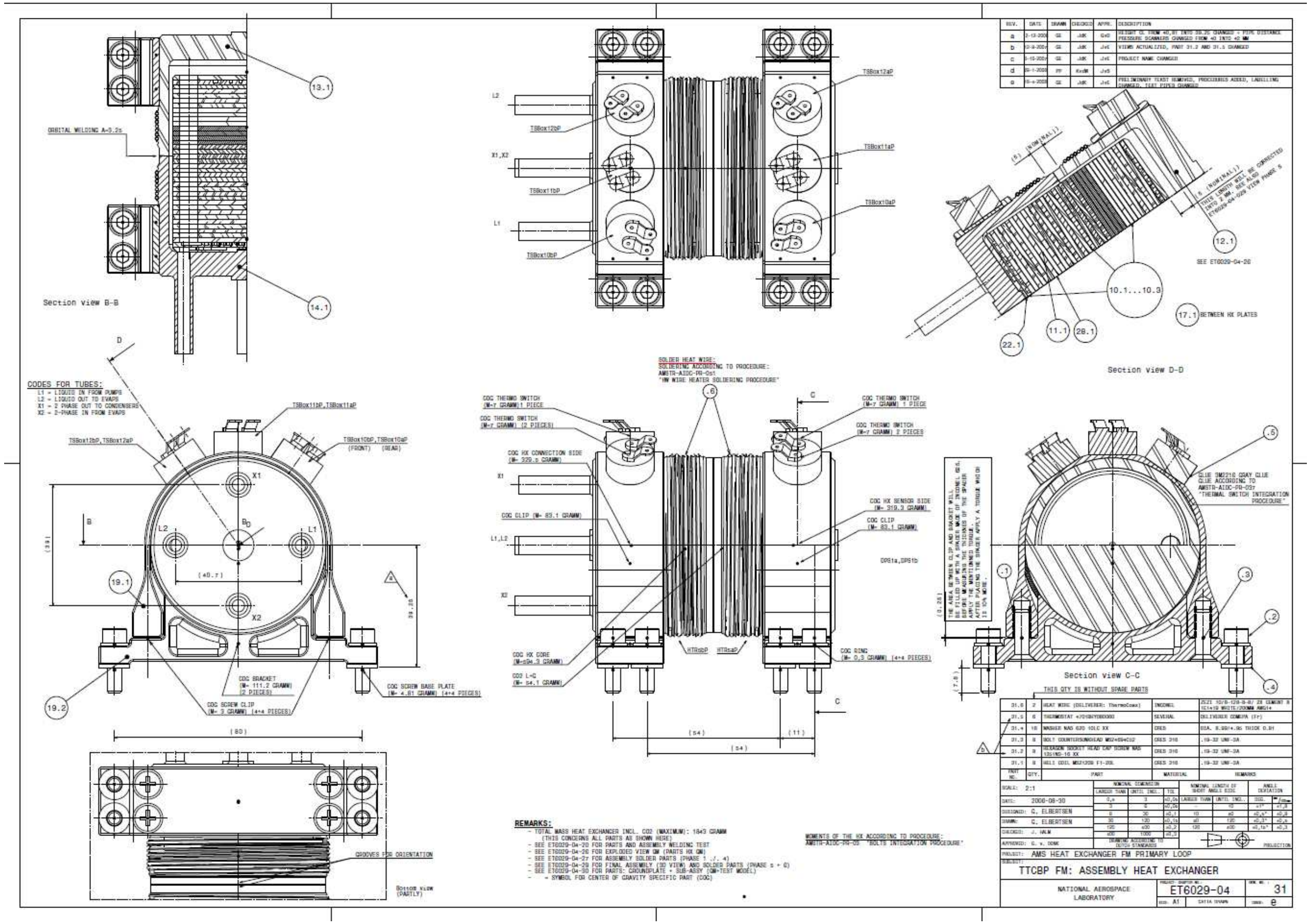
Appendix II: TTCS Orbital data installed on ISS

Run cases PRESENTED In this document	Beta Angle	Attitude	Suggested Env	Screening rank							
				TTCB-P 27100	TTCB-S 27200	RAM Rad Peak 81103	RAM Rad Avg 81103	WAKE Rad Peak 82103	WAKE Rad Avg 82103	Rad Avg	Delta T
1	75	-15-20-15	hot	H1		H5	H1			H1	
2	75	-15+00-15	hot	H2			H2			H2	
	75	-15+15-15	hot	H3			H3				
	30	+00-20-15	cold	C4	C2						
	0	-15+15-15	cold	C1							
	0	+00+00+00	cold	C2							
	-75	-15+25+15	hot		H1						4
	-75	-15+25+00	hot		H4						2
	-75	-15+15+15	hot		H2						7
	60	+15-20+00	cold		C1						
	30	-15-20-15	hot			H1	H7				
3	75	+15+15+15	cold			C1	C1				1
	-75	-15+25-15	cold		H6	C4	C2				5
	30	+15+25-15	hot					H1	H3	H4	
	-30	-15+25+15	hot					H2	H2		
	60	+15+25-15	hot					H4	H1	H7	
	75	-15+15+15	cold					C2	C2		
4	75	-15+00+15	cold		C6			C1	C1		
5	-75	+00+00-15	cold						C9	C1	
6	-75	+15+00-15	cold					C6	C5	C2	

Table 8-3: Extreme cases selection for operation

Notes: Hn means the n^{th} hottest case, Cn means the n^{th} coldest case. Delta T means the largest temperature difference between the two radiators.

Appendix III: TTCS HX Design



Appendix IV: TTCS Structural Verification Requirements Summary

A. Structural verification for flight components:

Ultimate load = Ultimate factor of safety x Limit load

Yield load = Yield factor of safety x Limit load

A1: The “Ultimate load” is the maximum load, which the structure must withstand without rupture.

A2: The “Yield load” is the load, which the structure must withstand without permanent deformation.

A3: The “Ultimate factor of safety” (FSu) and the “Yield factor of safety” (FSy) are the safety factors needed to calculate the “Ultimate loads” and “Yield loads.” These factors are:

Table 1:

No static testing required:

FSu = 2.0

FSy = 1.25

If the structure is static tested factors of safety can be reduced to:

FSu =1.40

FSy = 1.10

A4: The “Limit load” is the maximum load expected on the structure during its design service life. A simple way of defining the limit load is according the method from document: JSC 20545, Rev. A.

Limit load = Load factor x Weight

The load factor is according to table 2.

Table 2:

Component weight (lbs.)	Load factor (g)
<20	40
20-50	31
50-100	22
100-200	17
200-500	13

These load factors should be applied in any axis with a load factor equal to 25% applied to the 2 orthogonal axes simultaneously.

A5: All the hardware needs to have a first resonance frequency higher than 50 Hz, than no dynamic tests are required. If the resonance frequency is lower than 50 Hz but higher than 35 Hz, a sine sweep, smart hammer or modal testing is required.

B: Structural verification for pressurised systems:

Ultimate pressure = Ultimate pressure factor x MDP

B1: Where “MDP” stands for “Maximum Design Pressure”. MDP for a pressurised system shall be the highest pressure defined by the maximum relief pressure, maximum regulator pressure or maximum temperature.

B2: The “Ultimate pressure factor” is a multiplying factor applied to the MDP to obtain ultimate pressure. Pressurised components are to be designed to the following factors of safety.

Table3:

Lines and fittings:	Burst	Proof
Diameter <1.5”	*4.0*	*1.5*
Diameter =>1.5”	*2.5*	*1.5*
Other components	*2.5*	*1.5*

B3: In case of a pressurised system, the loads caused by the ultimate pressure needs to be added to the ultimate load caused by vehicle acceleration.

B4: To test the system for evidence of satisfactory workmanship, a proof pressure needs to be applied.

Proof pressure = Proof factor x MDP

The proof factor is determined in table 3.
Pressurised components shall sustain the proof pressure without detrimental deformation.

C: Fracture analysis:

C1: Pressurised components or sealed containers that have a non hazardous Leak-Before- Burst (LBB) mode of failure may be classified as low risk fracture parts.

C2: To classify mechanical fasteners as fail-safe it must be shown by analysis or test that the remaining structure after a single failure of the highest loaded fastener can withstand the loads with a factor of safety of 1.0

C3: Components in a sealed box do not need structural verification when it can be proved that the released parts are completely contained and will not cause a catastrophic hazard.

C4: All fasteners larger than M3 (US #8 and above) are subject to NASA structural testing. It is recommended to use NASA provided MS- or NASA- fasteners.

Appendix V: TTCS Box magnetic Field Map

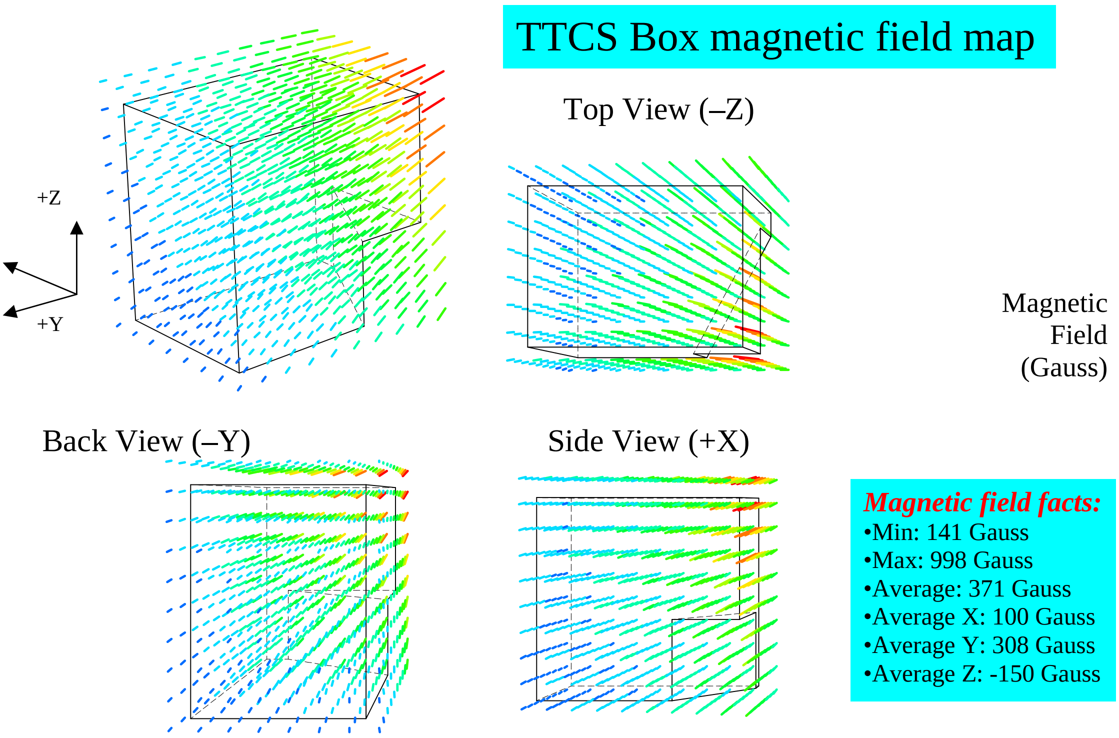


Figure 4: TTCS magnetic field map

Appendix V: TTCE Embedded S/W code

```
File TTCE_Data_Type3.txt
6 February 2008
FM/FS

TTEC-A has logical address 6C, TTEC-B has logical address 6D

Data Types:

 1.    x01   Read    Ping
 2.    x05   Write   Start Erase Flash Sector
 3.    x05   Read    Erase Status (NOT IMPLEMENTED)
 4.    x06   Read    Memory
 5.    x06   Write   Memory
 6.    x15   Write   Start DS Scan
 7.    x15   Read    DS Scan Status
 8.    x16   Read    DS Control Register
 9.    x16   Write   DS Control Register
10.    x17   Read    DS ID Table
11.    x17   Write   DS ID Table
12.    x18   Read    DS Temperatures
13.    x19   Read    Pt1000 Temperatures
14.    x19   Write   Pt1000 Redundancy Control
15.    x1A   Read    Pressure Sensors
16.    x07   Write   28V Control
17.    x07   Read    28V Control
18.    x08   Write   Pump Control
19.    x08   Read    Pump Control
20.    x09   Write   PWM Control
21.    x09   Read    PWM Control
22.    x03   Write   Execute Configuration File
23.    x1B   Write   Delay 10 msec
24.    x0A   Write   Loop Control
25.    x0A   Read    Loop Control


 1.   x01    Read    Ping
                     Request Data:  Length 0 - 8191 bytes
                     Reply: Length 0 - 8191 bytes, the same Data as in the Request

 2.   x05    Write   Start Erase Flash Sector
                     Request Data: Sector Number (0x0 - 0xF), one byte, only four LSbits used
                     Reply: Done if flash erase was started, abort if in Configuration file


 3.   x05    Read    Erase Status NOT IMPLEMENTED

                     Status of the erase sector number N operation can be found
                     reading memory at address 0x1N0000. The erase sector operation
                     has been completed if two consecutive reading data were equal.

 4.   x06    Read    Memory
                     Request Data: Bcnt1, Bcnt0, Addr2, Addr1, Addr0
                     Bcnt1 & Bcnt0 - Number of bytes to be read can be 0-8187
                     Addr2 & Addr1 & Addr0 - 21 bits memory start address
                     Reply: Bcnt1, Bcnt0, Addr2, Addr1, Addr0, memory data

 5.   x06    Write   Memory
                     Request Data: Bcnt1, Bcnt0, Addr2, Addr1, Addr0
                     Bcnt1 & Bcnt0 - Number of bytes to be written, can be 0-8186
                     Addr2 & Addr1 & Addr0 - 21 bits memory start address
                     Reply: Done if success, else Abort

 6.   x15    Write   Start DS Scan
                     Request Data: one byte, bit3->DS Bus3, bit2->DS Bus2,
                     bit1->DS Bus1, bit0->DS Bus0
                     Reply: Done

 7.   x15    Read    DS Scan Status
                     Request Data: None
                     Reply: Status in four LSbits, NDS0, NDS1, NDS2, and NDS3
                     NDSx - number of Dallas Sensors found at Bus x

 8.   x16    Read    DS Control Register
                     Request Data: None
                     Reply: one byte, four LSbits with DS Bus Enable

 9.   x16    Write   DS Control Register
                     Request Data: one byte, four DS Bus Enable LSbits
                     Reply: Done
```

10.	x17	Read	DS ID Table Request Data: one byte, only 2 LSbits, Bus Number Reply: one byte Bus Number, 8 x NDS bytes – DS IDs NDS - number of Dallas Sensors
11.	x17	Write	DS ID Table Request Data: one byte Bus Number, 8 x NDS bytes – DS IDs Reply: Done
12.	x18	Read	DS Temperatures Request Data: one byte, only 2 LSbits, Bus Number Reply: one byte Bus Number, 2 x NDS Temperature Two byte per DS First byte = signed char, temperature in ˚C Second byte: MSbit = 0 -> T is valid, MSbit = 1 -> Error, 4 LSbits = T in 1/16 of ˚C If Second byte MSbit = 0 then T[˚C] = First byte + Second byte/16.0
13.	x19	Read	Pt1000 Temperatures Request Data: None Reply: 44 bytes, 2x11 Prime Loop, 2x11 Secondary Loop Temperatures Two byte per T First byte = signed char, temperature in ˚C Second byte: 4 LSbits = 1/16˚C, bit 5 & bit4 Redundancy Control (RC), bit7 & bit6 Vote Result (VR) RC = 00->0(N), 01->1(L), 10->2(R), 11->Vote VR = 00->0(N), 01->1(L), 10->2(R), 11->Illegal T[˚C] = First byte + (Second byte & 0x0F)/16.0 Order of T values in reply:

T names	second byte Bits: 7,6	5,4
Pt01_P	VR	RC
Pt02_P	VR	RC
Pt03_P	VR	RC
Pt04_P	VR	RC
Pt05_P	VR	RC
Pt06_P	00	00
Pt07_P	00	00
Pt08_P	00	00
Pt09_P	00	00
Pt10_P	00	00
Pt11_P	00	00
Pt01_S	VR	RC
Pt02_S	VR	RC
Pt03_S	VR	RC
Pt04_S	VR	RC
P0t5_S	VR	RC
Pt06_S	00	00
Pt07_S	00	00
Pt08_S	00	00
Pt09_S	00	00
Pt10_S	00	00
Pt11_S	00	00

There are all Pt1000 readouts (ADC) in SRAM starting from address 0x050000
To read ALL Pt1000 sensors, data type Read Memory should be used.
Pt1000 readout (ADC) is 12 bits in two bytes:

First byte = 0000 & 4 MSbits
Second byte = LSB
REF0, REF1, REF2 - Precision resistor readout corresponding T=0°C
T[°C] = (Pt1000 readout - REF readout)/16.0
REF0 is reference for sensor i at address 0x050000 + 6*i
REF1 is reference for sensor i at address 0x050000 + 6*i + 2
REF2 is reference for sensor i at address 0x050000 + 6*i + 4
where i from 1 to 23
NC - Not Connected to PT1000
PtNNZP(S): NN - sensor number, Z = 0, 1, 2 (or N, L, R) redundant sensors
Z = _ not redundant sensors

REF0	0x050000	REF1	0x050002	REF2	0x050004
Pt010P	0x050006	Pt011P	0x050008	Pt012P	0x05000A
Pt020P	0x05000C	Pt021P	0x05000E	Pt022P	0x050010
Pt030P	0x050012	Pt031P	0x050014	Pt032P	0x050016
Pt040P	0x050018	Pt041P	0x05001A	Pt042P	0x05001C
Pt050P	0x05001E	Pt051P	0x050020	Pt052P	0x050022
Pt06_P	0x050024	Pt07_P	0x050026	Pt08_P	0x050028
Pt09_P	0x05002A	Pt10_P	0x05002C	Pt11_P	0x05002E
NC	0x050030	NC	0x050032	NC	0x050034
Pt010S	0x050036	Pt011S	0x050038	Pt012S	0x05003A
Pt020S	0x05003C	Pt021S	0x05003E	Pt022S	0x050040
Pt030S	0x050042	Pt031S	0x050044	Pt032S	0x050046
Pt040S	0x050048	Pt041S	0x05004A	Pt042S	0x05004C
Pt050S	0x05004E	Pt051S	0x050050	Pt052S	0x050052
Pt06_S	0x050054	Pt07_S	0x050056	Pt08_S	0x050058
Pt09_S	0x05005A	Pt10_S	0x05005C	Pt11_S	0x05005E
NC	0x050060	NC	0x050062	NC	0x050064
NC	0x050066	NC	0x050068	NC	0x05006A
NC	0x05006C	NC	0x05006E	NC	0x050070
NC	0x050072	NC	0x050074	NC	0x050076
NC	0x050078	NC	0x05007A	NC	0x05007C
NC	0x05007E	NC	0x050080	NC	0x050082
NC	0x050084	NC	0x050086	NC	0x050088
NC	0x05008A	NC	0x05008C	NC	0x05008E

14. x19 Write Pt1000 Redundancy Control
Request Data: One byte per Redundant Temperature Measurement Point
Reply: Done
Can be from 1 to 10 Data bytes
bit3 & bit2 & bit1 & bit0 =address, 0_9 valid
bit5 & bit4 = 00->0(N), 01->1(L), 10->2(R), 11-Vote

15. x1A Read Pressure Sensors
Request Data: None
Reply: 8 bytes, APS_P, DPS_P, APS_S, DPS_S
Two byte per pressure sensor
First byte = 8 MSbits
Second byte: bit3 & bit2 & bit1 & bit0 = 4LSbits

16. x07 Write

28V Control
Request Data: 8 bytes
Reply: Done
There are 16 different heaters each powered by 28V through two switches (E, M) connected in series.
There is control bit for each switch. Control bit = 0 - switch is OFF, control bit = 1 - switch is ON.
Control bit can be set according rule:
If (Write Enable bit == 1) then Control bit = Set value

Switch	Set value		Write Enable bit	
name	byte & bit		byte & bit	
E_LLW_P	0	0	2	0
E_LLR_P	0	1	2	1
E_PR1_P	0	2	2	2
E_PR2_P	0	3	2	3
E_COR_P	0	4	2	4
E_SUP_P	0	5	2	5
E_GAE_P	0	6	2	6
E_FAE_P	0	7	2	7
M_LLW_P	1	0	2	0
M_LLR_P	1	1	2	1
M_PR1_P	1	2	2	2
M_PR2_P	1	3	2	3
M_COR_P	1	4	2	4
M_SUP_P	1	5	2	5
M_GAE_P	1	6	2	6
M_FAE_P	1	7	2	7
E_LLW_S	3	0	5	0
E_LLR_S	3	1	5	1
E_PR1_S	3	2	5	2
E_PR2_S	3	3	5	3
E_COR_S	3	4	5	4
E_SUP_S	3	5	5	5
E_GAE_S	3	6	5	6
E_FAE_S	3	7	5	7
M_LLW_S	4	0	5	0
M_LLR_S	4	1	5	1
M_PR1_S	4	2	5	2
M_PR2_S	4	3	5	3
M_COR_S	4	4	5	4
M_SUP_S	4	5	5	5
M_GAE_S	4	6	5	6
M_FAE_S	4	7	5	7

There are 6 regulated voltage (PWM) loads powered by 28V through one switch each and 2 pump 28V switches :

Switch	Set value		Write Enable bit	
name	byte & bit		byte & bit	
E_GAC_P	6	0	7	0
E_FAC_P	6	1	7	1
E_TEC_P	6	2	7	2
E_GAC_S	6	3	7	3
E_FAC_S	6	4	7	4
E_TEC_S	6	5	7	5
P_P	6	6	7	6
P_S	6	7	7	7

```
17.    x07    Read    28V Control
                      Request Data:  None
                      Reply: 5 bytes with values of Control bits for each switch:

                      Switch        Control bit
                      name            byte & bit

                      E_LLW_P          0    0
                      E_LLR_P          0    1
                      E_PR1_P          0    2
                      E_PR2_P          0    3
                      E_COR_P          0    4
                      E_SUP_P          0    5
                      E_GAE_P          0    6
                      E_FAE_P          0    7

                      M_LLW_P          1    0
                      M_LLR_P          1    1
                      M_PR1_P          1    2
                      M_PR2_P          1    3
                      M_COR_P          1    4
                      M_SUP_P          1    5
                      M_GAE_P          1    6
                      M_FAE_P          1    7

                      E_LLW_S          2    0
                      E_LLR_S          2    1
                      E_PR1_S          2    2
                      E_PR2_S          2    3
                      E_COR_S          2    4
                      E_SUP_S          2    5
                      E_GAE_S          2    6
                      E_FAE_S          2    7

                      M_LLW_S          3    0
                      M_LLR_S          3    1
                      M_PR1_S          3    2
                      M_PR2_S          3    3
                      M_COR_S          3    4
                      M_SUP_S          3    5
                      M_GAE_S          3    6
                      M_FAE_S          3    7

                      E_GAC_P          4    0
                      E_FAC_P          4    1
                      E_TEC_P          4    2
                      E_GAC_S          4    3
                      E_FAC_S          4    4
                      E_TEC_S          4    5
                      P_P              4    6
                      P_S              4    7

18.    x08    Write   Pump Control
                      Request Data: 2 byte
                      Reply: Done
                      Byte 0  SCV_P   Speed Control Voltage for Pump in Prime Loop
                      Byte 1  SCV_S   Speed Control Voltage for Pump in Secondary Loop
                      Control Voltage V = 4096 * (SCV Code / 256) [mV]

19.    x08    Read    Pump Control
                      Request Data: None
                      Reply: 6 bytes
                                          Byte
                      SCV_P               0
                      SCV_S               1
                      PPS_P   8MSbits     2
                      PPS_P   4LSbits     3 (bit3 & bit2 & bit1 & bit0)
                      PPS_S   8MSbits     4
                      PPS_S   4LSbits     5 (bit3 & bit2 & bit1 & bit0)

                      SCV - Speed Control Voltage
                      PPS - Pulse per second
                      Pump speed (RPM) = PPS / 9.0 * 60.0
```

```
20.     x09     Write   PWM Control
                        Request Data: from 2 to 12 byte
                        Reply: Done
                        Two bytes per PWM controller
                        Byte0 - Address (0..5 valid)
                        Byte1 - DCV Duty Cycle Value
                        PWM controller output is 0V (OFF) if DCV=0
                        Duty Cycle 99.6% if DCV=255
                                        Address
                        DCV_GAC_P       0
                        DCV_FAC_P       1
                        DCV_TEC_P       2
                        DCV_GAC_S       3
                        DCV_FAC_S       4
                        DCV_TEC_S       5

21.     x09     Read    PWM Control
                        Request Data: None
                        Reply: 6 byte
                                        Byte
                        DCV_GAC_P       0
                        DCV_FAC_P       1
                        DCV_TEC_P       2
                        DCV_GAC_S       3
                        DCV_FAC_S       4
                        DCV_TEC_S       5

22.     x03     Write   Execute Configuration File
                        Request Data: None
                        Reply: Done if configuration file execution complete,
                        Abort if configuration file check sum test error or recursive execution
                        The Log file contains execution details.

                Configuration file should be written into flash memory starting from address 0x100000
                (it is flash sector #0).

                Configuration file format:

                        Request length MSB              // first request
                        Request length LSB
                        Request Data Type
                        Request Data
                        ...
                        Request length MSB              // last request
                        Request length LSB
                        Request Data Type
                        Request Data
                        0x00                            // zero length
                        0x00
                        CKS MSB                         // Configuration file Check Sum
                        CKS LSB

                Log file format (in memory starting from 0x040000):

                        Request length MSB              // first executed request
                        Request length LSB
                        Request Data Type
                        Request Data
                        Status                          // request execution status
                        ...
                        Request length MSB              // last executed request
                        Request length LSB
                        Request Data Type
                        Request Data
                        Status                          // request execution status
                        0x00
                        0x00

                        Status = 0 if request done, status = 1 if request abort
```

```
Configuration file is executed when:
        1. TTCE was OFF and power (28V) is applied to TTCE
        2. TTCE receives Execute Configuration file request (0x03)

 Configurations file execution actions:

 // Check Sum test. CKS is unsigned 16-bit, memory( ) is unsigned char

        address = 0x100000;
        CKS = 0;
    a:  CKS = CKS + memory(address) + memory(address + 1);
        length = 256 * memory(address) + memory(address + 1);
        address = address + 2;
        if (length != 0 & address < 0x1040000) {
          for (i=0; i<length; i++; address++) CKS = CKS + memory(address);
          goto a;
        }
        If (address >= 0x1040000) abort;
        If (CKS != 256 * memory(address) + memory(address + 1)) {
          abort;
        }

 // Execution

        address = 0x100000;
        log_addr = 0x040000;
    b:  length = 256 * memory(address) + memory(address + 1);
        if (length != 0 & address < 0x1040000) {
          memory(log_addr) = memory(address);    // copy request length to log
          memory(log_addr + 1) = memory (address + 1);
          log_addr = log_addr + 2;
          address = address + 2;
          request = address;
          for (i=0; i<length; i++; log_addr++; address++) //copy request to log
            memory(log_addr) = memory(address);
          result = EXECUTE(length, request, WRITE); //force abort for READ request
          If (result == abort) memory(log_addr) = 1; else memory(log_addr) = 0;
          log_addr = log_addr + 1;
          goto b;
        }
        done;
```

23.	x1B	write	Delay 10 msec Request Data: None Reply: Done after 10 msecond Can be used in configuration file to provide delay between operations

24.	x0A	Write	Loop Control Request Data: from 2 to 128 bytes Reply: Done Two bytes per parameter Byte0 - Address (0...63 valid) Byte1 - Parameter Value
25.	x0A	Read	Loop Control Request Data: None Reply: 64 bytes One byte per parameter Read only bit/bytes marked RO Read and Clear bits marked RC

Parameters for Primary Loop (0 – x1F)

x00	Control	bits5-4:range, 3:heat RO, 2:FG, 1:test, 0:pi_enable
x01	Set_point	bits5-0: accumulator set point (-32°C - 31°C)
x02	k1	Unsigned 8-bit, LSbit = 1 (0 - 255)
x03	k2	Unsigned 8-bit, LSbit = 1/16 (0 - 15.9375)
x04	k3	Unsigned 8-bit, LSbit = 1/32 (0 - 7.96875)
x05	iband	Unsigned 8-bit, LSbit = 1/16°C (0 - 3.9375°C)
x06	Feed_forw	MSB, Signed 16-bit (-32768 - 32767)
x07	Feed_forw	LSB
x08	Test_T	4MSbits=0, bits3-0 contain bits 11-8 of Test_T
x09	Test_T	bits7-0 of Test_T, LSbit = 1/16°C (-128°C - +127.9375°C)
x0A	ph_term	RO MSB, signed 16-bit
x0B	ph_term	RO LSB
x0C	ih_term	RO MSB, signed 16-bit
x0D	ih_term	RO LSB
x0E	pi_dcv	RO Unsigned char
x0F	cav_magine	bits4-0, LSbit = 1/2°C (0 - 15.5°C)
x10	LLW_Loop	bit7:out RO, 6:enable, 5-0:set point (-32°C - 31°C)
x11	LLR_Loop	bit7:out RO, 6:enable, 5-0:set point (-32°C - 31°C)
x12	PR1_Loop	bit7:out RO, 6:enable, 5-0:set point (-4°C - 3.875°C)
x13	PR2_Loop	bit7:out RO, 6:enable, 5-0:set point (-4°C - 3.875°C)
x14	COR_Loop	bit7:out RO, 6:enable, 5-0:set point (-32°C - 31°C)
x15	SUP_Loop	bit7:out RO, 6:enable, 5-0:set point (-32°C - 31°C)
x16	alarm_ena	7:GAC, 6:LPS, 5:LLR, 4:LLW, 3:PR2, 2:PR1, 1:TRK, 0:CAV
x17	alarm_now	RO all 7:GAC, 6:LPS, 5:LLR, 4:LLW, 3:PR2, 2:PR1, 1:TRK, 0:CAV
x18	alarm_was	RC all 7:GAC, 6:LPS, 5:LLR, 4:LLW, 3:PR2, 2:PR1, 1:TRK, 0:CAV
x19	cycle_cnt	RC number of tmperature measurement cycles after last read
x1A	Not defined	RO
x1B	Not defined	RO
x1C	Not defined	RO
x1D	Not defined	RO
x1E	Not defined	RO
x1F	Not defined	RO

x20 - x3F set of the same parameters for Secondary Loop

```
Power-On default values for Loop Control:

 x00 Control        range=0, FG=1, test=0, pi_enable=0
 x01 Set_point      0'C
 x02 k1             16      16
 x03 k2             0x10    1.0
 x04 k3             0x10    0.5
 x05 iband          0x10    1'C
 x06 Feed_forw      0
 x07 Feed_forw      0
 x08 Test_T         0       0.0'C
 x09 Test_T         0
 x0A ph_term        depend on Pt01_P
 x0B ph_term        depend on Pt01_P
 x0C ih_term        0
 x0D ih_term        0
 x0E pi_dcv         depend on Pt01_P
 x0F cav_margin     0x0A     5'C
 x10 LLW_Loop       0x20  -31'C, enable=0, out=0
 x11 LLR_Loop       0x20  -31'C, enable=0, out=0
 x12 PR1_Loop       0x20   -4'C, enable=0, out=0
 x13 PR1_Loop       0x20   -4'C, enable=0, out=0
 x14 COR_Loop       0x20  -31'C, enable=0, out=0
 x15 SUP_Loop       0x20  -31'C, enable=0, out=0
 x16 alarm_ena      0xFF  All alarms are enabled
 x17 alarm_now      depend on Pt01_P - Pt09_P
 x18 alarm_was      depend on Pt01_P - Pt09_P
 x19 cycle_cnt      # of cycles after power-on (modulo 256)
 x1A Not defined    0
 x1B Not defined    0
 x1C Not defined    0
 x1D Not defined    0
 x1E Not defined    0
 x1F Not defined    0

 x20 - x3F set of the corresponding parameters for Secondary Loop
```

```
Loop Control parameters are the settings and monitoring values which provide
automatic control over:

1. Accumulator Heaters and Peltiers
2. Liquid Line Health Heaters
3. Preheaters
4. Cold Orbit Heaters
5. Start-up Heaters
6. Alarms (health guards)

TTCE measures temperatures and evaluates new settings for PWM and ON/OFF control
every cycle = 0.786432 seconds.

Primary Loop Parameters x00-x0E (x20-x2E for Secondary Loop) are used in Accumulator
temperature PI regulation.

Primary Loop Parameters x10-x15 (x30-x35 for Secondary Loop) are used in ON/OFF
loop control for Liquid Line Health Heaters (LLW & LLR), Preheaters (PR1 & PR2),
Cold Orbit Heater (COR), Start-up Heater (SUP).

Primary Loop Parameters x0F, x16-x18 (x2F, x36-x38 for Secondary Loop) are used
for Alarms control.
```

pi_enable	if pi_enable = 1 then pi_dcv is used for Accumulator/Peltier PWM control else DCV_GAC, DCV_FAC, DCV_TEC are used.
test	if test = 1 then Test Temperature value is substituted instead of measured temperature Pt01.
FG	if FG = 1 then Flight Accumulator Control (FAC) Heater will be used else Ground Testing Accumulator Control (GAC) Heater will be used.
heat	if heat = 1 then Accumulator Control (FAC or GAC) Heater will be used else Peltier will be used.
range	P-term lineare range (0: ±3.9375°C, 2: ±1.9375°C , 1: ±0.9375°C)
Set_point	accumulator set point, bits5-0, LSbit=1°C (-32°C - +31°C)
k1	proportional term coefficient (0 - 255)
k2	integral term coefficient, LSbit=1/16 (0 - 15.9375)
k3	peltier coefficient, LSbit=1/32 (0 - 7.96875)
iband	If the temperature is in the range Set_point ± iband and pi_enable=1 then the error is integrated else i_term = 0. LSbit = 1/16°C (0 - 3.9375°C).
Feed_forw	constant term to compensate known heat leak (-32768 - 32767)
Test_T	the temperature which is used in test mode (test=1) signed 12-bit, LSbit = 1/16°C (-128°C - +127.9375°C).
ph_term	proportional term divided by two, ph_term = p_temt/2 signed 16-bit (-32768 - 32767)
ih_term	integral term divided by two, ih_term = i_temt/2 signed 16-bit (-32768 - 32767).
pi_dcv	duty cycle value which is used for PWM control of Accumulator Heater (0-240, heat=1) or Peltier (0-127, heat=0) if pi_enable=1
cav_margin	Minimum allowable differance between Accumulator Set_point and Pump inlet temperature (Pt02). There is cavitation alarm (CAV) if Set_point < Pt02 + cav_margin
LLW_enable	enable Liquid Line WAK heater (LLW) loop control
LLW_set_point	LLW loop control set point (-32°C - 31°C)
LLW_out	LLW loop control output. if (LLW_set_point > Pt09) LLW_out = 1; else LLW_out = 0; If LLW_out = 1 and LLW loop is enabled (LLW_enable = 1) and there is no active LLW alarm (LLW_alarm_act = 0) and there is no active Cavitation alarm (CAV_alarm_act = 0) then LLW heater is ON.
LLR_enable	enable Liquid Line RAM heater (LLR) loop control
LLR_set_point	LLR loop conrol set point (-32°C - 31°C)
LLR_out	LLR loop control output. if (LLR_set_point > Pt06) LLR_out = 1; else LLR_out = 0; If LLR_out = 1 and LLR loop is anabled (LLR_enable = 1) and there is no active LLR alarm (LLR_alarm_act = 0) and there is no active Cavitation alarm (CAV_alarm_act = 0) then LLR heater is ON.
PR1_enable	enable Preheater 1 (PR1) loop control
PR1_set_point	PR1 loop conrol set point (-4°C - 3.875°C)
PR1_out	PR1 loop control output. if (Set_point + PR1_set_point > Pt04) PR1_out = 1; else PR1_out = 0; If PR1_out = 1 and PR1 loop is anabled (PR1_enable = 1) and there is no active PR1 alarm (PR1_alarm_act = 0) and there is no active Cavitation alarm (CAV_alarm_act = 0) and there is no active

```
Alarms definitions:

if (Set_point < Pt02 + cav_margin) CAV_alarm_now = 1; else CAV_alarm_now = 0;
if (Pt04 >  20°C || Pt05 >  20°C ||
    Pt04 < -20°C || Pt05 < -20°C ) TRK_alarm_now = 1; else TRK_alarm_now = 0;
if (Pt04 > 35°C)                   PR1_alarm_now = 1; else PR1_alarm_now = 0;
if (Pt05 > 35°C)                   PR2_alarm_now = 1; else PR2_alarm_now = 0;
if (Pt09 > 35°C)                   LLW_alarm_now = 1; else LLW_alarm_now = 0;
if (Pt06 > 35°C)                   LLR_alarm_now = 1; else LLR_alarm_now = 0;
if (Pump Speed < 2400rpm)          LSP_alarm_now = 1; else LSP_alarm_now = 0;
if (Pt03 > 45°C)                   GAC_alarm_now = 1; else GAC_alarm_now = 0;

Alarms actions:

if (XXX_alarm_now == 1 && XXX_alarm_ena == 1) XXX_alarm_act = 1; else XXX_alarm_act = 0;


if (CAV_alarm_act == 1 && Set_point < 25°C) Set_point = MIN(Pt02 + cav_magin, 25°C);
if (CAV_alarm_act == 1) {LLW OFF; LLR OFF; PR1 OFF; PR2 OFF; COR OFF; SUP OFF;}
if (TRK_alarm_act == 1) ;
if (PR1_alarm_act == 1) PR1 OFF;
if (PR2_alarm_act == 1) PR2 OFF;
if (LLW_alarm_act == 1) LLW OFF;
if (LLR_alarm_act == 1) LLR OFF;
if (LPS_alarm_act == 1) {PR1 OFF; PR2 OFF; COR OFF; SUP OFF; TEC_DCV=0;}
if (GAC_alarm_act == 1) GAC OFF;


ON/OFF loop control formulas (executed every cycle = 0.786432 seconds):

if (            LLW_set_point > Pt09) LLW_out = 1; else LLW_out = 0;
if (            LLR_set_point > Pt06) LLR_out = 1; else LLR_out = 0;
if (Set_point + PR1_set_point > Pt04) PR1_out = 1; else PR1_out = 0;
if (Set_point + PR2_set_point > Pt05) PR2_out = 1; else PR2_out = 0;
if (            COR_set_point > Pt02) COR_out = 1; else COR_out = 0;
if (            SUP_set_point > Pt04) SUP_out = 1; else SUP_out = 0;

Accumulator PI regulation formulas (executed every cycle = 0.786432 seconds):

error_T = Set_point - measured_T;  // LSbit = 1/16°C, (±3.9375°C)

abs_error_T = ABS(error_T);  // (0 - 3.9375°C)

if (abs_error_T < iband) in_iband = 1; else in_iband = 0;

if     (error_T > 0.9375°C && range == 1) {error_T = 0.9375°C; big_p_err = 1;}
elseif (error_T <-0.9375°C && range == 1) {error_T =-0.9375°C; big_n_err = 1;}
elseif (error_T > 1.9375°C && range == 2) {error_T = 1.9375°C; big_p_err = 1;}
elseif (error_T <-1.9375°C && range == 2) {error_T =-1.9375°C; big_n_err = 1;}
elseif (error_T > 3.9375°C)               {error_T = 3.9375°C; big_p_err = 1;}
elseif (error_T <-3.9375°C)               {error_T =-3.9375°C; big_n_err = 1;}
else {big_p_err = 0; big_n_err = 0;}

p_term = 4 * R * K1 * error_T; //(±64260), R=4 if range=1, R=2 if range=2, else R=1

if (in_iband = 1 & enable = 1)
        i_term = i_term + k2/16 * error_T; else i_term = 0; // (±65535)

pi_val = p_term + i_term + Feed_forw; // (±65535)

if (pi_val >= 0) heat = 1; pi_abs = pi_val; else heat = 0; pi_abs = -pi_val;

pi_tec = k3/32/256 * pi_abs; // (0 - 2047)

pi_heat = SQRT(pi_abs);   // (0 - 255)  sqrt to compensate fact that P ~ U * U

if (pi_tec > 127 || big_n_err == 1) pi_tec = 127; // Limit to 13.7V

if (pi_heat > 240 || big_p_err == 1) pi_heat = 240; // PWM works unstable if DC > 95%

if (heat == 1) pi_dcv = pi_heat; else pi_dcv = pi_tec;
```